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THESIS

PERFORMANCE ANALYSIS OF MANAGEMENT TECHNIQUES FOR SONET/SDH TELECOMMUNICATIONS NETWORKS

by

Hwee Ping Ng

March 2005

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13. ABSTRACT (maximum 200 words)

The performance of network management tools for SONET/SDH networks subject to the load conditions is studied and discussed in this thesis. Specifically, a SONET network which consists of four CISCO ONS 15454s, managed by a CISCO Transport Manager, is set up in the Advanced Network Laboratory of the Naval Postgraduate School. To simulate a realistic data transfer environment for the analysis, Smartbits Avalanche software is deployed to simulate multiple client-server scenarios in the SONET network. Traffic from the management channel is then captured using a packet sniffer. Queuing analysis on the captured data is performed with particular emphasis on properties of self-similarity. In particular, the Hurst parameter which determines the captured traffic's degree of self-similarity is estimated using the Variance-Index plot technique. Link utilization is also derived from the computation of first-order statistics of the captured traffic distribution. The study shows that less management data was exchanged when the SONET network was fully loaded. In addition, it is recommended that CTM 4.6 be used to manage not more than 1552 NEs for safe operation. The results presented in this thesis will aid network planners to optimize the management of their SONET/SDH networks.

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PERFORMANCE ANALYSIS OF MANAGEMENT TECHNIQUES FOR SONET/SDH TELECOMMUNICATIONS NETWORKS

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The performance of network management tools for SONET/SDH networks subject to the load conditions is studied and discussed in this thesis. Specifically, a SONET network which consists of four CISCO ONS 15454s, managed by a CISCO Transport Manager, is set up in the Advanced Network Laboratory of the Naval Postgraduate School. To simulate a realistic data transfer environment for the analysis, Smartbits Avalanche software is deployed to simulate multiple client-server scenarios in the SONET network. Traffic from the management channel is then captured using a packet sniffer. Queuing analysis on the captured data is performed with particular emphasis on properties of self-similarity. In particular, the Hurst parameter which determines the captured traffic's degree of self-similarity is estimated using the Variance-Index plot technique. Link utilization is also derived from the computation of first-order statistics of the captured traffic distribution. The study shows that less management data was exchanged when the SONET network was fully loaded. In addition, it is recommended that CTM 4.6 be used to manage not more than 1552 NEs for safe operation. The results presented in this thesis will aid network planners to optimize the management of their SONET/SDH networks.

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EXECUTIVE SUMMARY

The growth in Internet has led to an unprecedented shift in traffic behavior, pattern and content. This trend has inadvertently resulted in a surge in the demand of bandwidth for the consumer market. Similarly, there is also an anticipated increase in the bandwidth for military operations and deployments. With the paradigm shift from platform-centric warfare to network-centric warfare to leverage information superiority, it is crucial to put in place a fully automated and reliable network for the warfighters.

The Synchronous Optical Network (SONET) standard in North America and the Synchronous Digital Hierarchy (SDH) standard – the international equivalent of SONET – are seen as enabling technologies to fulfill the worldwide growing bandwidth demand in the commercial market. As more and more optical networks are deployed to meet this bandwidth demand, more sophisticated management tools are required to ensure proper optimization of network resources and end-to-end reliability. Unfortunately, the bandwidth allocated for management of these next generation optical networks is constrained.

In this study, the effect of traffic loading on the performance of Element Management System (EMS) that is used for managing SONET/SDH networks is investigated. The results obtained will aid in understanding how well the management system will scale when operating in conjunction with a heavy traffic load.

For the purpose of this study, a SONET network was set up in the Advanced Network Laboratory at the Naval Postgraduate School. The network management tool deployed was the Cisco Transport Manager (CTM) version 4.6. In addition, Spirent's Avalanche Smartbits, a traffic generator, was installed and configured to generate user traffic on the SONET ring. Data was then passively captured from the CTM 4.6 server via Ethereal, a packet sniffer. Note that only Socks, SNMPv2 and TCP traffic from CTM 4.6 were relevant for the detailed analysis.

The results gathered from Ethereal were compared to the findings obtained in Ref. [5]. Preliminary observation showed that less traffic was exchanged between the CTM and the managed NEs when the SONET network is loaded. Close inspection revealed

that more Socks and SNMP traffic were transferred when there is no user traffic on the network.

Further analysis on the inter-arrival time and packet size distribution were performed. From the inter-arrival distribution, all the traffic (Socks, SNMPv2 and Ethernet traffic) demonstrated long range dependence and self-similarity, regardless of the load conditions in the SONET network. However, it was observed that management data was exchanged at a shorter time interval without user traffic in the SONET network. For the packet size distribution, it was found that the packet size of all traffic were very similar under different load conditions.

The Hurst parameter (H) was then used to estimate the self-similarity of all the traffic. Using the Variance-Index Plot approach, large values of H were found for all traffic, thus indicating that the traffic is self-similar and bursty in nature. These results were similar to Ref. [5] except for Socks and combined Socks and SNMP traffic.

The link utilization was derived for all the traffic collected. In particular, CTM 4.6's Socks and SNMP traffic had a link utilization of 0.612 when CTM 4.6 is used to manage 2500 network elements (NEs). This value was much lower compared to the high utilization of 0.926 obtained in Ref. [5] under no-load condition in the SONET network. Though the utilization was lower in the case of having user traffic in the network, the high Hurst parameter value computed may pose a problem for the CTM 4.6 to manage the 2500 NEs.

A network utilization versus queue depth graph was plotted to determine the number of NEs that the CTM is capable of managing, taking into account the burstiness of the traffic. From the plot, it is recommended that the CTM 4.6 manages up to a maximum of 1552 NEs, operating within a utilization of 0.38 under load conditions in the SONET network to prevent queuing buffer overflow (compared to 1027 NEs under the no-load condition in the SONET network).

LIST OF SYMBOLS, ACRONYMS, AND/OR ABBREVIATIONS

Alcatel	Alcatel Network Systems
ARP	Address Resolution Protocol
Avalanche	Avalanche Smartbits
CISCO	Cisco Systems
CORBA	Common Object Request Broker Architecture
CTC	CISCO Transport Controller
CTM 4.6	CISCO Transport Manager 4.6
DNS	Domain Name Server
EMSs	Element Management Systems
Gbps	gigabits-per-second
GIOP	General Inter–Orb Protocol
GUI	Graphical User Interface
H	Hurst parameter
HTTP	Hypertext Transfer Protocol
IDs	Identifications
IETF	Internet Engineering Task Force
IOS	Internet Operating System
IP	Internet Protocol
ISO	International Standardization for Organization
ITU-T	International Telecommunication Union–Telecommunication Standardization Bureau
kbps	kilobits-per-second

log	logarithmic function
Lucent	Lucent Technologies
Marconi	Marconi Communications
M/M/1	System with exponential inter-arrival and service times
Mbps	megabits-per-second
Micromuse	Micromuse Inc.
ms	milliseconds
NEC	NEC Transmission
NEs	Network Elements
NPS	Naval Postgraduate School
OAM&P	Operations, Administration, Maintenance, and Provisioning
ONS 15454	Optical Network System 15454
OS	Operating System
PC	Personal Computer
POS	Packet-over-SONET
Q	queue depth
s	seconds
SDCC	Section Data Communication Channel
SDH	Synchronous Digital Hierarchy
SNMP	Simple Network Management Protocol
SNMPv2	Simple Network Management Protocol Version 2
SONET	Synchronous Optical Network
Spirent	Spirent Communications

TCP	Transport Control Protocol
TL1	Transaction Language 1
T_S	service time
UDP	User Datagram Protocol
μ_X	mean
σ_X	standard deviation
λ	mean arrival rate in items per second
μs	microseconds
ρ	network utilization

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I. INTRODUCTION

A. MOTIVATION

The world is publishing and, in turn, consuming the large quantities of data on the Internet. According to the August 2004 bandwidth report, US broadband penetration broke 50% in July 2004 [1]. Indeed, the growth in Internet has led to an unprecedented shift in traffic behavior, pattern and content. This trend has inadvertently resulted in a surge in the demand of bandwidth for the consumer market.

Similarly, there is also an anticipated increase in the bandwidth for military operations and deployments. With the paradigm shift from platform-centric warfare to network-centric warfare to leverage information superiority, it is crucial to put in place a fully automated and reliable network for the warfighters [2].

The Synchronous Optical Network (SONET) standard in America and the Synchronous Digital Hierarchy (SDH) standard – the international equivalent of SONET – are seen as enabling technologies to fulfill the growing bandwidth demand. Currently, SONET/SDH is capable of supporting a line rate of up to 40 gigabits-per-second (Gbps) at OC-768 [3]. As more and more optical networks are deployed to meet the bandwidth demand, more sophisticated management tools are required to ensure proper optimization of network resources and end-to-end reliability. Unfortunately, the bandwidth allocated for management of these next generation optical networks is constrained. It is not well-understood how well these management systems will scale when operating in conjunction with a heavy traffic load. It will therefore be worthwhile to analyze the nature of traffic produced by management tools and their ability to manage large networks under fully loaded conditions.

B. THESIS OBJECTIVE

The primary objective of this thesis was to study and analyze the effect of traffic loading on the performance of Element Management System (EMS) that is used for managing SONET/SDH networks. A SONET network with traffic generated using the Avalanche Smartbits from Spirent Communications [4] was simulated under laboratory con-

ditions with a commercial EMS running. Based on the network load captured from the EMS, a statistical analysis was then performed. As a follow-up to the thesis by Wee Siong Lim [5], the focus of this thesis was to compare and model the statistical nature of network traffic generated by the Cisco Transport Manager (CTM) version 4.6 for self-similarity with and without traffic in the SONET ring. The number of optimum number of Network Elements (NEs) was also determined based on the derived results.

C. RELATED WORK

There is significant research in the general area of network management. Much of the contemporary research is not focusing on the management of the network and protocols employed for the network management. Rather, the research today involves studying the performance of network management as more functions are embedded into the intelligent network elements [6, 7]. In addition, the industries are also looking into the development of network management across multiple service providers and across multiple technologies (e.g. Marconi [8], Telcordia [9]).

Within the Naval Postgraduate School (NPS), one of the research focuses for the Advanced Networking Laboratory has been in the arena of network management, in particular on SDH/SONET networks. Recent work by Kok Seng Lim [10], which studied the effect of SNMP traffic on Network Management Systems (NMS), showed that a NMS can effectively manage a network with less than 200 NEs. Additional laboratory research by Wee Shoong Lim [5] recommended using the CTM for managing up to 1027 NEs in SDH/SONET network operating within a link utilization of 38% that can be supported by a reasonably-sized queuing buffer. Lim's analysis was performed without any user traffic transiting the managed switches. Consequently, it did not consider management traffic in a realistic, operational environment. Although SONET/SDH management traffic is exchanged in an out-of-band channel from user traffic and thus has no direct impact on user metrics, it is useful to examine whether a fully loaded network will cause the transiting switches to generate management messages at a different time interval and of different length than when no user traffic at all is being passed on the network.

D. SUMMARY

The organization of the thesis is as follows: Chapter II discusses the SONET network management tool and SNMP protocol used with a focus on the Cisco Transport Manager 4.6 (CTM 4.6). Chapter III describes the procedures for setting up the laboratory SONET network, the Avalanche Smartbits, the EMS, and the capturing of the network load used in this study. Chapter IV briefly reviews queuing theory and the concept of self–similarity. Chapter V presents the traffic analysis done on the captured traffic and discusses the results obtained. Chapter VI concludes the study and provides suggestions on further research areas.

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II. SONET NETWORK MANAGEMENT TOOL

A. CHAPTER OVERVIEW

This chapter gives an overview on the network management protocols with a focus on the Simple Network Management Protocol (SNMP) used in our CISCO equipment. The chapter then continues to provide readers an insight on CISCO Transport Manager (CTM) Release 4.6 tool used in the laboratory set-up.

B. INTRODUCTION

Early SONET vendors adopted the standard transaction language 1 (TL1) interface from Bellcore (now Telcordia) to perform operation, administration, maintenance and provisioning (OAM&P) [3]. The drawback for TL1 is that it requires a man in the loop to gather relevant information and perform routine diagnostic checks. With the increased complexity in the SONET network, the need for automation in network management becomes essential. Many vendors including the six main SONET/SDH equipment manufacturers: Alcatel Network Systems (Alcatel), Fujitsu Network Transmission Systems (Fujitsu), Lucent Technologies (Lucent), NEC Transmission (NEC), Nortel Networks, and Tellabs, instead build their own software to manage their SONET equipment and nodes [5]. In addition to these vendor-specific protocols, the International Standardization for Organization (ISO), International Telecommunications Union – Telecommunications (ITU-T) and Internet Engineering Task Force (IETF) also developed separate open standard network management protocols.

C. SNMP

SNMP was first developed in 1988 by the IETF to manage nodes in the IP network and has since become the de facto standard for internetwork management. As the name implies, it is a simple solution with minimal code for implementation. In addition, its extensibility allows vendors to easily build additional management functions to their existing products. SNMP also separates the management architecture from the architec-

ture of the hardware devices, which broadens the base of multi-vendor support [11]. The latest version of SNMP is SNMPv3.

Common to both SNMP Version 1 and SNMPv2 is a set of management commands and responses (*get, getNext, set* and *trap*). Figure 1 summarizes the details of each command in SNMPv2. Illustrated in the figure, the *get, getNext, getBulk* and *set* commands are issued by the management system to retrieve single or multiple object variables. The managed agent responds to complete the commands. To identify an occurrence of an event, a *trap* command is used. Of significance to SNMPv2, compared to its previous version, is its improved security features and its ability to handle a huge volume of management data via the *getBulk* command [12].

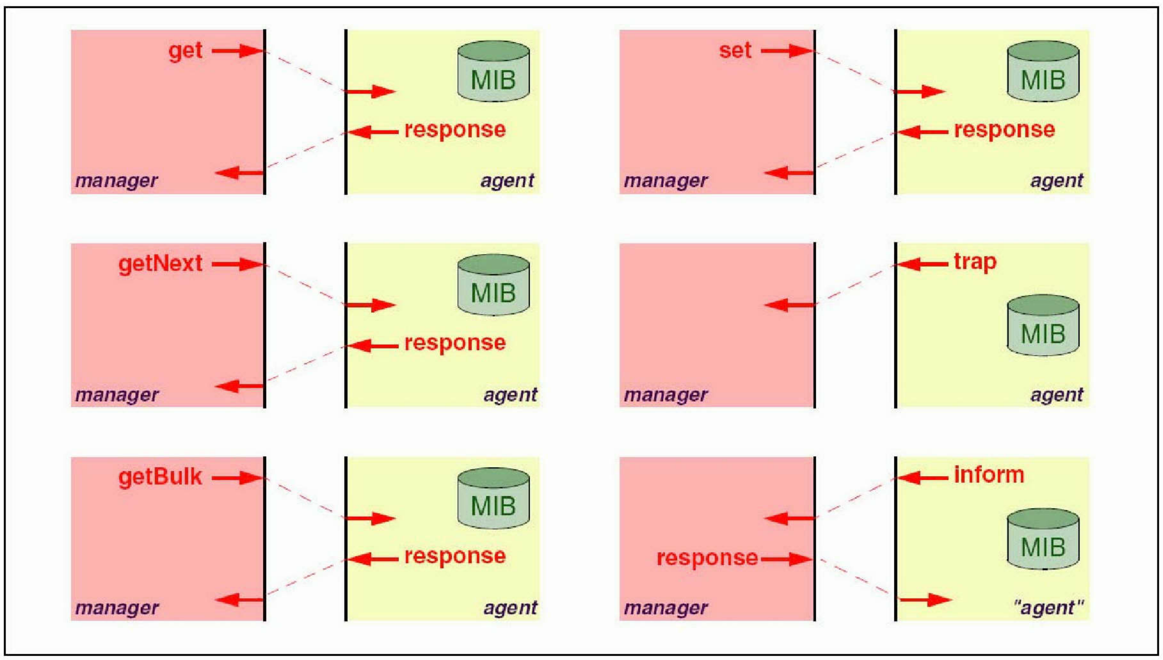

Figure 1. SNMPv2 protocol operations (From Ref. [12].)

D. CTM 4.6

CTM 4.6 is the element management system (EMS) for the CISCO Optical Network System (ONS) 15000 series product line [13]. For the purpose of our study, the CISCO ONS 15454, with the capability for supporting high speed optical and gigabit

networking, was used. Via SNMPv2, CTM 4.6 collects its network information from CISCO Transport Controller (CTC), an EMS shipped with the ONS 15454.

As the most advanced optical EMS for Cisco ONS 15000 series products, CTM 4.6 can scale up to 2500 NEs and 100 concurrent clients. It provides a variety of graphical user interfaces (GUI) namely the domain explorer, network map, NE explorer and alarm browser. Figures 2 to 5 show examples of screenshots of each GUI. The domain explorer, Figure 2, provides a logical view of the network plus alarm, connectivity, and operational status. Administrators use the domain explorer to create groups of NEs and to organize the domain in a hierarchy. The network map, Figure 3, displays the geographical layout of the network. Node position, node icons and background map images can be customized in this view. The NE explorer window, Figure 4, presents equipment-provisioning information about the selected NE. Based on the user's selection of the NE, this configuration information is retrieved through CORBA, SNMP or TL1. The alarm browser display, Figure 5, presents alarms and conditions in the managed domain. Each alarm is categorized into various levels of severity (e.g. critical, major, minor or warning). In addition to the GUI and management functions, CTM 4.6 also supports an extensive collection of performance statistics across the network for export or display.

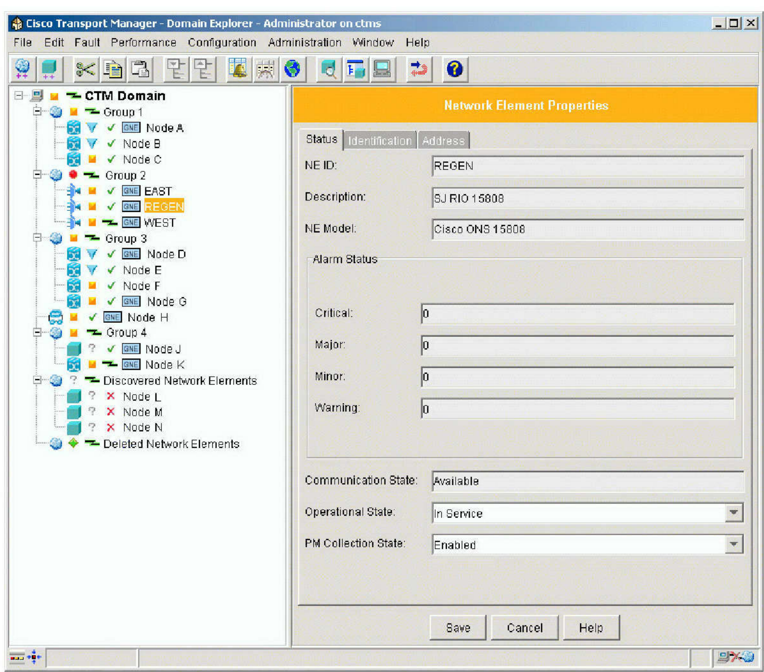

Figure 2. Screenshot of domain explorer (From Ref. [14].)

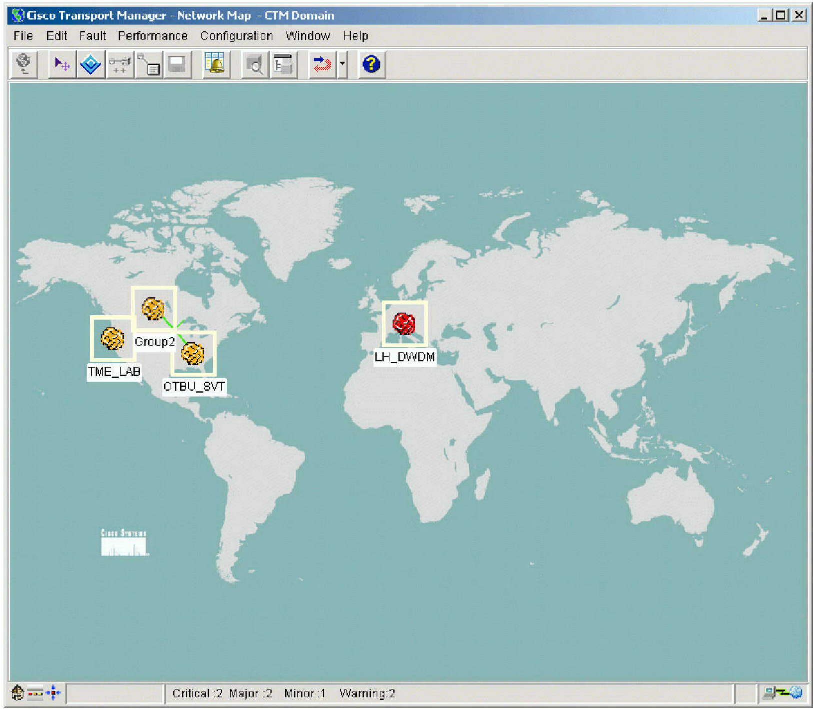

Figure 3. Screenshot of network map (From Ref. [14].)

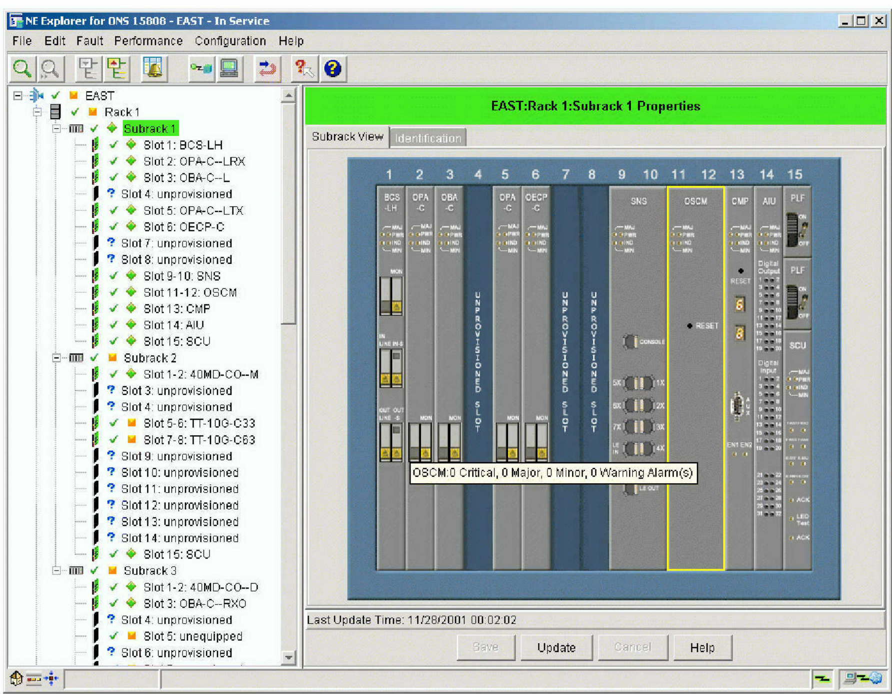

Figure 4. Screenshot of NE explorer (From Ref. [14].)

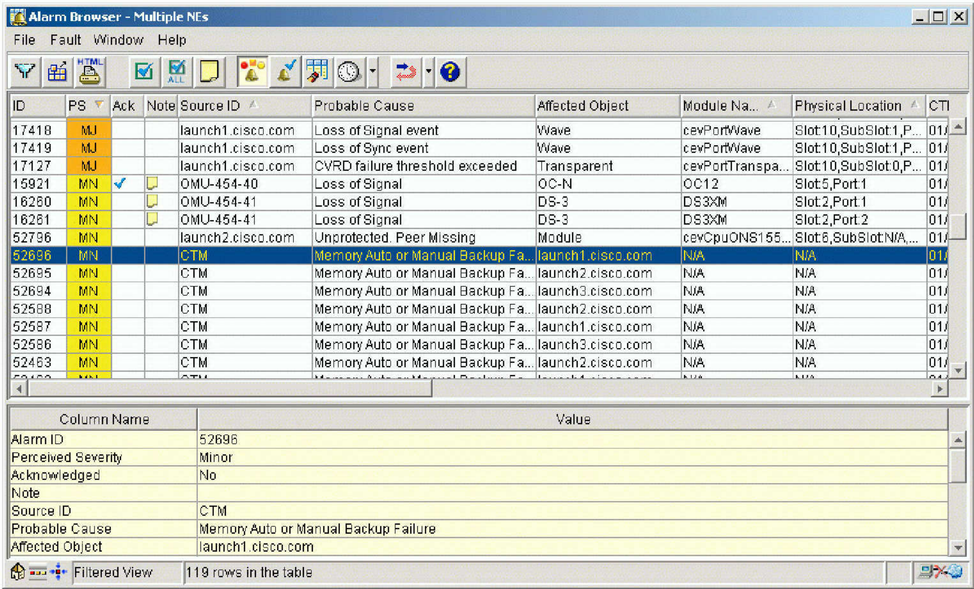

Figure 5. Screenshot of alarm browser (From Ref. [14].)

E. SUMMARY

The SNMP protocol was discussed in this chapter and the differences between SNMP and SNMPv2 were highlighted. An overview of CTM 4.6 was also provided to give insight to the product used in the set-up.

The next chapter describes the SONET network and Avalanche configuration in the laboratory and the procedures which were performed to capture the data for analysis.

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III. LABORATORY SET-UP AND PROCEDURES

A. CHAPTER OVERVIEW

This chapter describes the SONET network and equipment configuration in the laboratory which includes the installation steps and challenges faced during the set-up. Next, the chapter will discuss the procedures performed to collect data for analysis.

B. LABORATORY SET-UP

Figure 6 shows the logical implementation of the SONET network and Avalanche Smartbits in the Advanced Networking Laboratory.

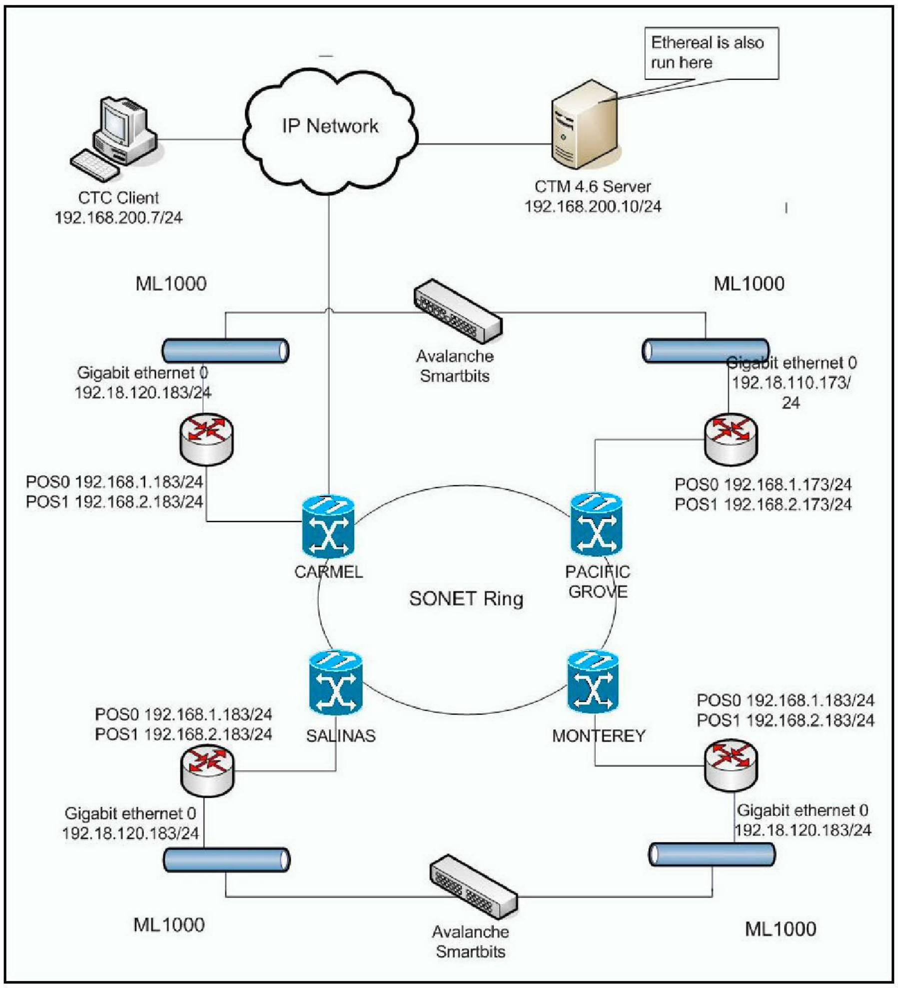

Figure 6. Logical implementation of the Advanced Network Laboratory's SONET network with simulated traffic loading

As seen from Figure 6, the SONET network is formed by four ONS 15454s connected in a ring. Each ONS is connected to the Avalanche Smartbits via the multi-layered ethernet card ML-1000. In addition, one of the ONS15454 is connected to an IP network which acts as a bridge between the IP and SONET networks.

C. EQUIPMENT CONFIGURATION

1. Installing ONS 15454s

The four ONS 15454s in Advanced Networking Laboratory were installed by Lieutenant Mathew Klobukowski. These four ONS were connected in the ring to form the SONET network and configured to simulate a regional network. Each ONS was assigned a NE Identification (ID) and IP address as shown in Table 1. Link tests were conducted and it was found that one of the links between the ONS15454s was down. Reconfiguration on that particular link was then performed.

NE ID	IP Address
Carmel	192.168.200.210
Pacific Grove	192.168.200.211
Monterey	192.168.200.212
Salinas	192.168.200.213

Table 1. NE ID and IP address assignment

2. Installing the ML-1000

The ML-1000, a gigabit Ethernet card, was installed in each ONS15454 to provision the Ethernet interface for Avalanche Smartbits. The ML-1000 card was configured via the console port. In this case, an adaptor is required to connect to the console port as an RJ-11 interface is used instead of the typical RJ-45 interface. Upon connection, a "no shutdown" command was issued at the command prompt of the CISCO IOS such that the interfaces available are no longer "administratively down".

Next, the link aggregation for the ML-1000 card (both gigabit Ethernet and Packet-over-SONET (POS) channels) was configured. IP addresses were assigned to

the gigabit Ethernet and POS interfaces as shown in Table 2. Table 3 illustrates an example of the configuration of the ML-1000. After the configuration was completed, a "show interface" command allowed the status of the interface to be monitored as shown in Figure 7. In addition, ping commands were executed to ensure that the links between the gigabit-ethernet and the POS interface across ONS15454s were configured correctly.

Host Name	IP Address		
	gigabitethernet 0	POS 0	POS1
Carmel	192.168.120.183/24	192.168.1.183/24	192.168.2.183/24
Monterey	192.168.100.183/24	192.168.1.163/24	192.168.2.163/24
Pacific Grove	192.168.110.183/24	192.168.1.173/24	192.168.2.173/24
Salinas	192.168.90.183/24	192.168.1.153/24	192.168.2.153/24

Table 2. IP addresses for interface of each ML-1000

ML-1000 Configuration
hostname Monterey ! interface gigabitethernet 0 ip address 192.18.110.163 255.255.255.0 no shutdown ! interface gigabitethernet 1 no ip address ! interface POS 0 ip address 192.168.1.163 255.255.255.0 crc 32 ! interface POS 1 ip address 192.168.2.163 255.255.255.0 crc 32 ! ip route 0.0.0.0 0.0.0.0 pos0 !

Table 3. Configuration of ML-1000

```
Router# show int gigabitethernet 0
Gigabitethernet0 is up, line protocol is up
Hardware is FEChannel, address is 0005.9a39.6634 (bia 0000.0000.0000)
MTU 1500 bytes, BW 200000 Kbit, DLY 100 usec,
reliability 255/255, txload 1/255, rxload 1/255
Encapsulation ARPA, loopback not set
Keepalive set (10 sec)
Unknown duplex, Unknown Speed
ARP type: ARPA, ARP Timeout 04:00:00
No. of active members in this channel: 2
Member 0 : FastEthernet0 , Full-duplex, Auto Speed
Member 1 : FastEthernet1 , Full-duplex, Auto Speed
Last input 00:00:01, output 00:00:23, output hang never
Last clearing of "show interface" counters never
Input queue: 0/150/0/0 (size/max/drops/flushes); Total output drops: 0
Queueing strategy: fifo
Output queue :0/80 (size/max)
5 minute input rate 0 bits/sec, 0 packets/sec
5 minute output rate 0 bits/sec, 0 packets/sec
820 packets input, 59968 bytes
Received 0 broadcasts, 0 runts, 0 giants, 0 throttles
0 input errors, 0 CRC, 0 frame, 0 overrun, 0 ignored
0 watchdog, 0 multicast
0 input packets with dribble condition detected
32 packets output, 11264 bytes, 0 underruns
0 output errors, 0 collisions, 0 interface resets
0 babbles, 0 late collision, 0 deferred
0 lost carrier, 0 no carrier
0 output buffer failures, 0 output buffers swapped out.
```

Figure 7. Screenshot of status monitoring of an interface

3. Installing CTM 4.6

Mr. Wee Shoong Lim set up the CTM 4.6 server, Oracle 8i, CTM database schema and CTM web server on the Sun Solaris 8 Operating System (OS) in the Advanced Network Laboratory. In addition, SNMPv2 was also enabled on ONS15454 as it is the underlying protocol for CTM 4.6 as shown in Figure 8. As indicated on Figure 8, SNMPv2 was configured to use the community name "AdvNetLab" and the UDP port 162 for sending SNMPv2 traps to the CTM 4.6 server (IP address – 192.168.200.10). The "Maximum Trap per Second" was also set to 0 such that all traps are sent to the CTM 4.6 server.

Next the CTM 4.6 client was installed onto a PC running Windows XP. The NEs to be monitored by the CTM 4.6 server were added through the CTM 4.6 client and the performance monitoring option in the CTM 4.6 was enabled. Finally, to verify that the CTM server was running, a "showctm" command was executed. Processes like "CTMServer", "SNMPTrapService" and "SMService" as shown in Figure 9 indicate that the server is up and running.

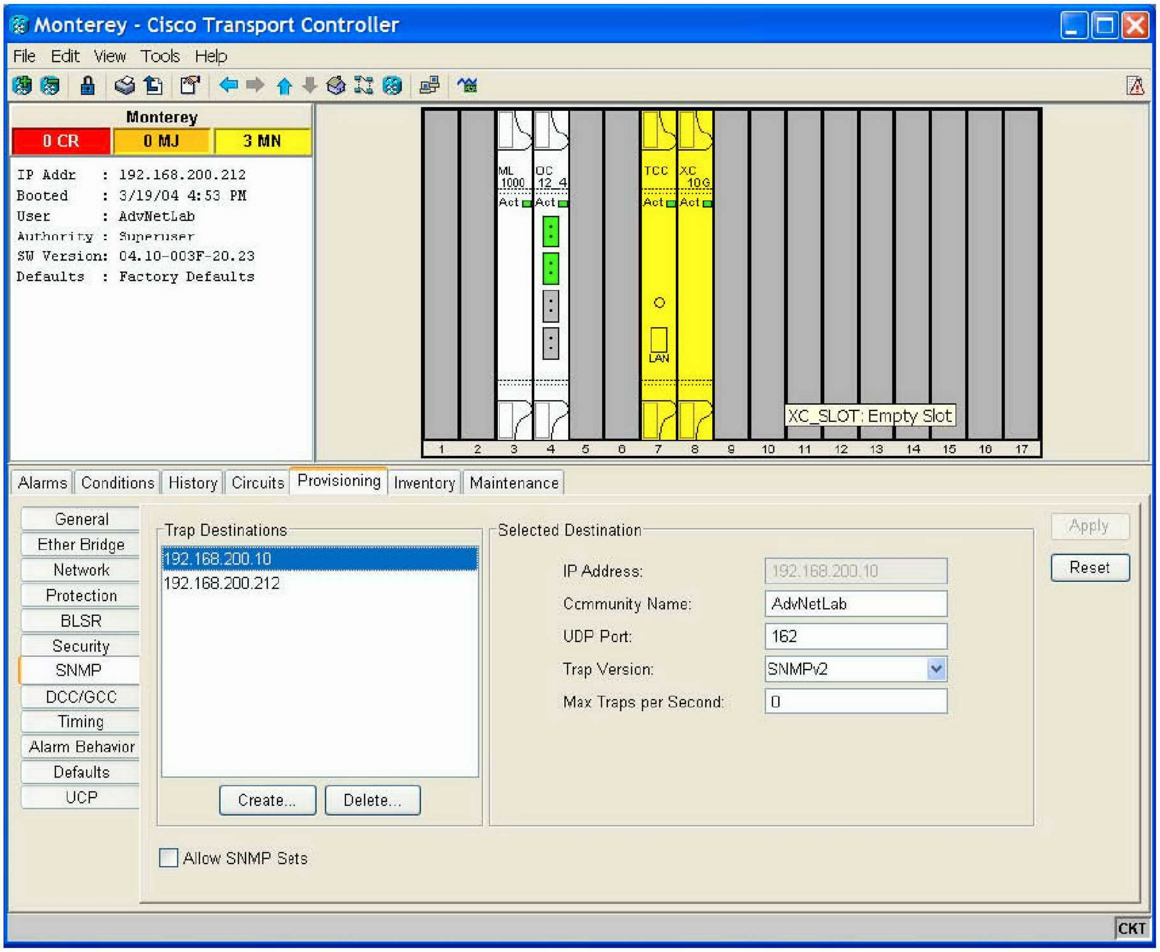

Figure 8. ONS15454s' SNMPv2 configuration (From Ref. [5].)

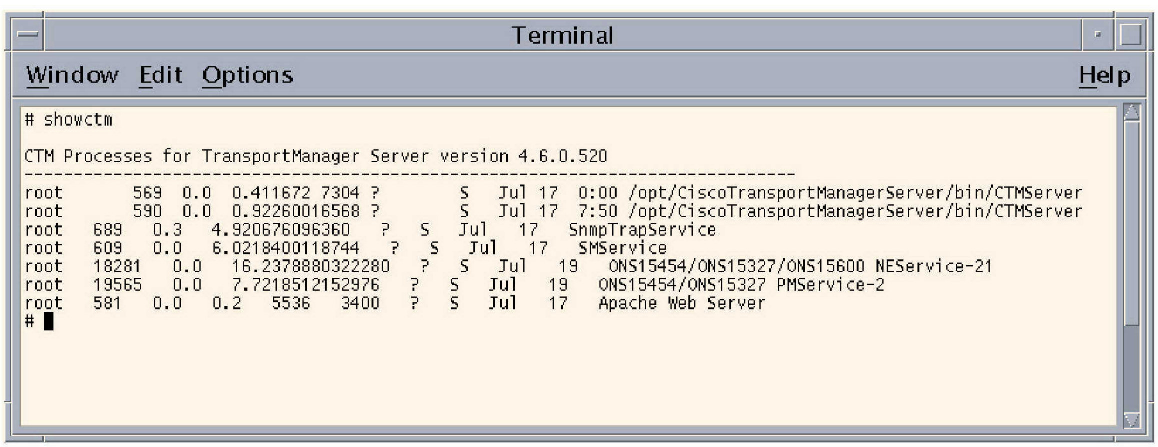

Figure 9. CTM processes running on the server (From Ref. [5].)

4. Installing Avalanche Smartbits

In this study, the Avalanche SmartBits, a performance analysis test platform developed by Spirent Technology, was chosen to emulate traffic on the SONET ring. Figure 10 illustrates the various levels one can choose from for configuring the Avalanche system to meet their testing requirements. The Avalanche system allows easy emulation of client-server environments. Various test files can be loaded for simulations. Some of the test specifications that can be configured through the GUI include load constraints, random error generation and network profiles (e.g., TCP retries and routing). For device testing, various interfaces can be specified. Subnet addressing can also be specified for simulating large network infrastructures. In addition, the Avalanche system allows simulating different user characteristics through *user profiles*. Each user profile is then correlated with a set of associated test files to simulate many simultaneous users in the Avalanche environment [15].

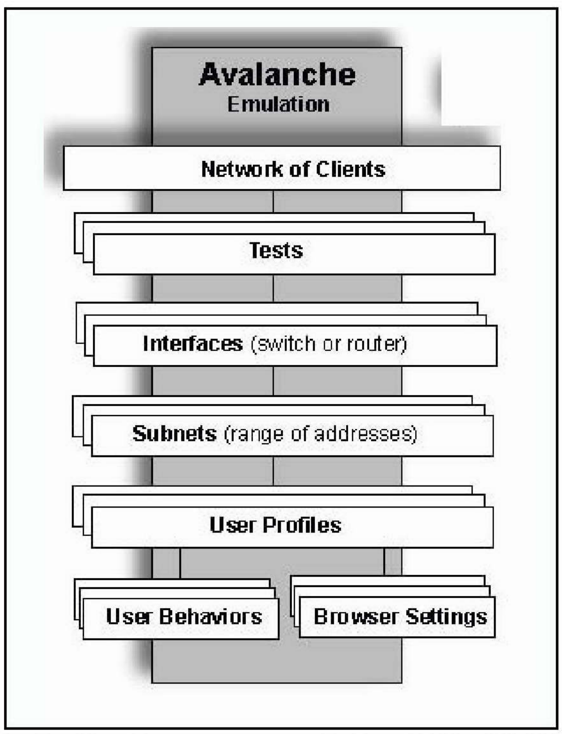

Figure 10. Avalanche system emulation (After Ref. [15].)

Figure 11 shows the set-up of the Avalanche Smartbits hardware in the laboratory. The chassis, which housed the TeraMetrics gigabit Ethernet interface cards, was

connected to the network via the Ethernet port found on the chassis backplane. In this case, an IP address of 192.168.200.150 was assigned to the chassis via the console port.

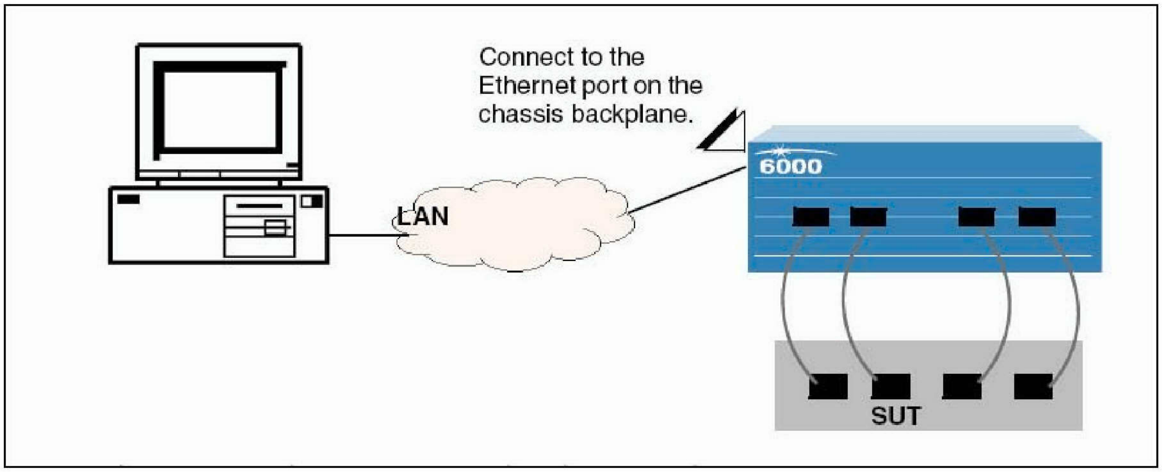

Figure 11. Set-up of Avalanche hardware (From Ref. [9].)

The Avalanche software was then installed. Using the Smartbits chassis administration window each TeraMetrics module was configured. Figure 12 shows the configuration set-up in the Smartbits chassis administration window

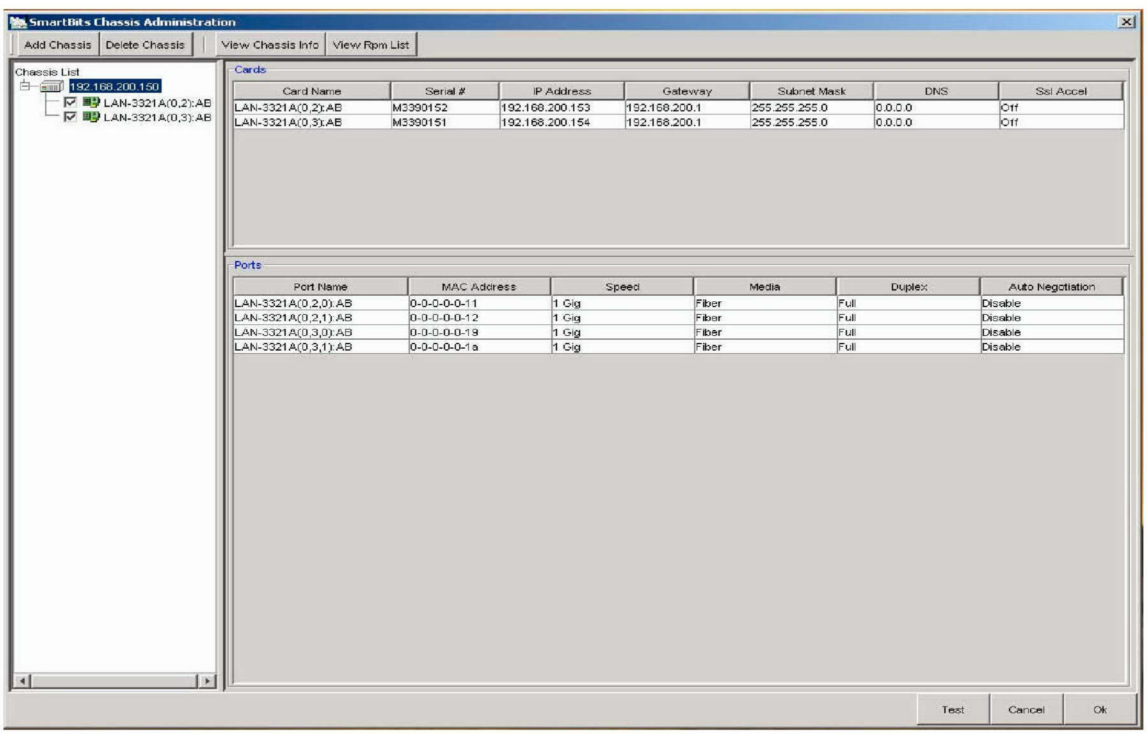

Figure 12. Configuration set-up in the Smartbits chassis administration window

Next, client-server scenarios were defined in the Avalanche software to simulate the traffic loading in the SONET network as shown in Figure 13. As seen in the figure, Carmel and Salinas were configured to be connected to a hundred clients each. HTTP servers were configured to be connected to Pacific Grove and Monterey.

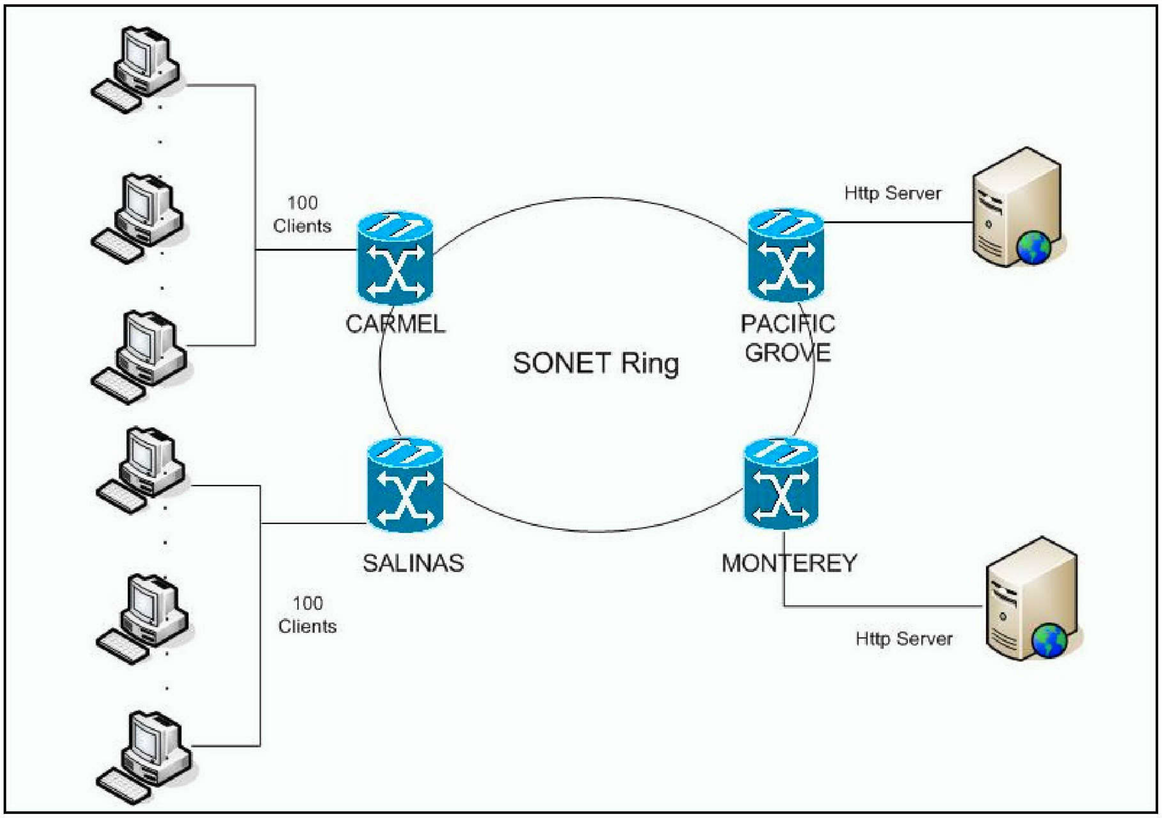

Figure 13. Client-server scenarios

Figure 14 shows the screenshot of the GUI to define the clients' IP addresses. A similar GUI is used to define the IP addresses of the server. Traffic was then generated by the Web connections from clients to the HTTP servers. Figure 15 shows the set-up of the client actions to access the HTTP server in the user profile.

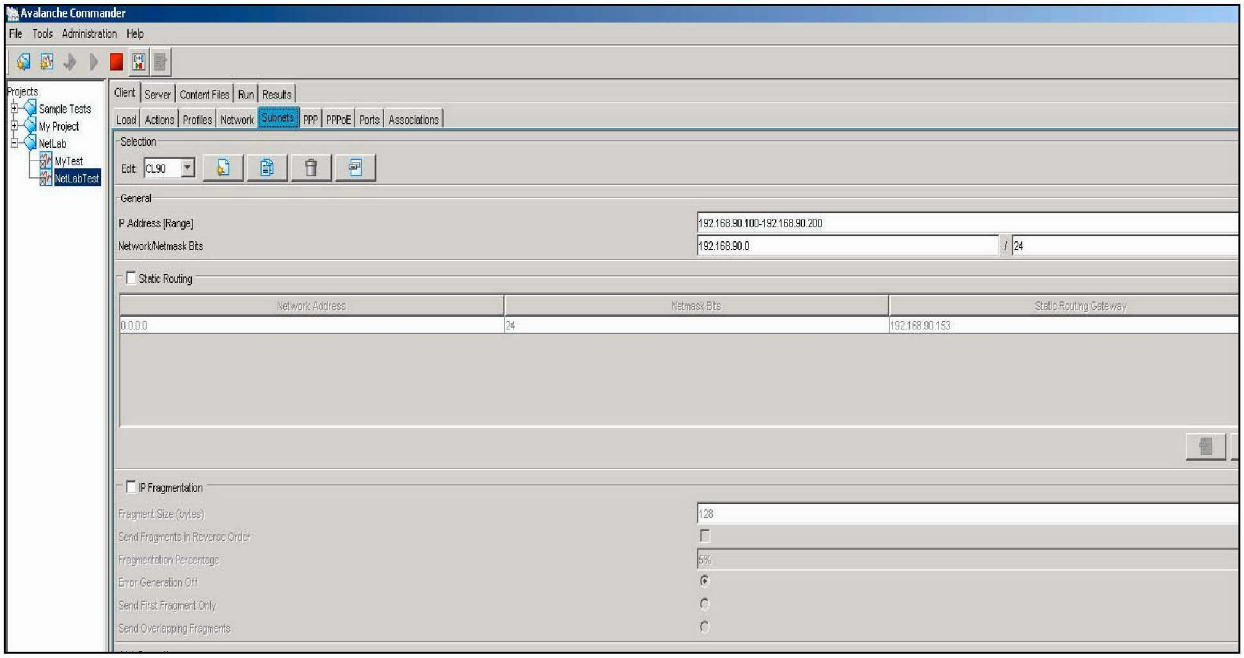

Figure 14. Screenshot of the GUI to define the clients' IP addresses

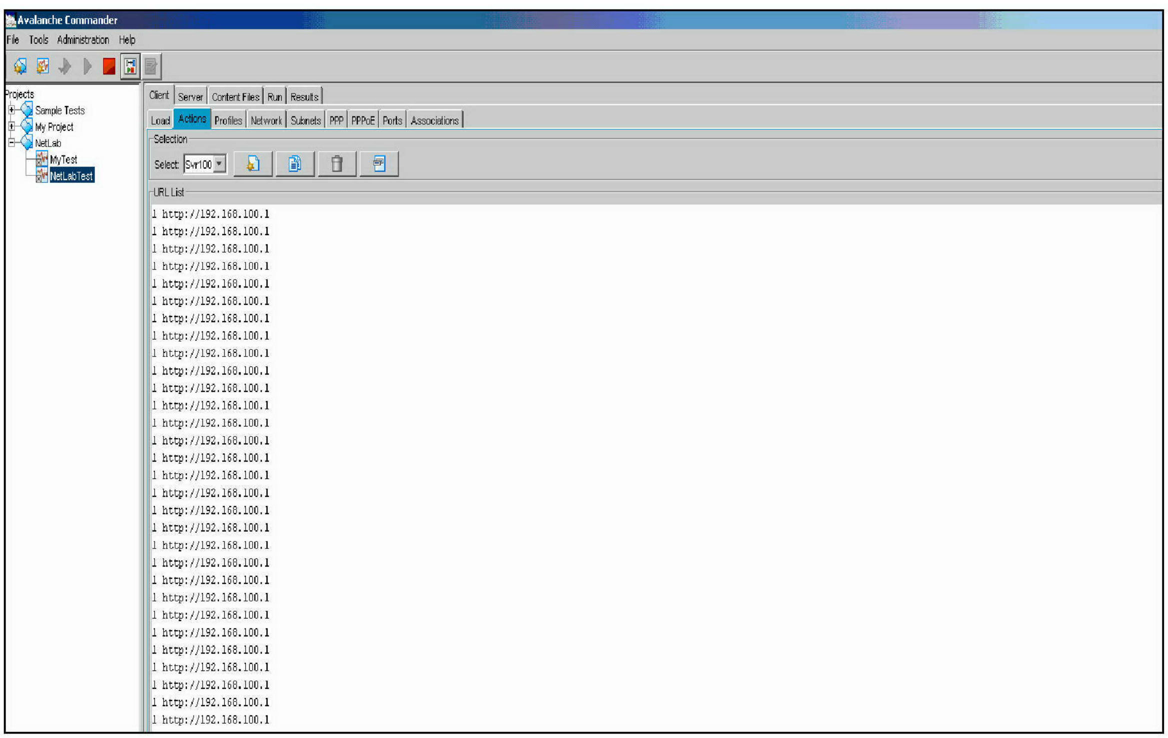

Figure 15. Screenshot of a client profile to access the HTTP server

D. DATA COLLECTION

Ethereal, an open source packet sniffer program, was used to capture the desired data for analysis. As seen in Figure 1, Ethereal was installed in the same machine as the CTM 4.6 Server to passively capture incoming and outgoing traffic from the CTM. The traffic includes management data of all network elements and SNMPv2 traps sent to the Server. In this study, the CTM Server was left running for a period of 10 days to generate sufficient data for analysis. Figure 16 shows a screenshot of the data captured using Ethereal.

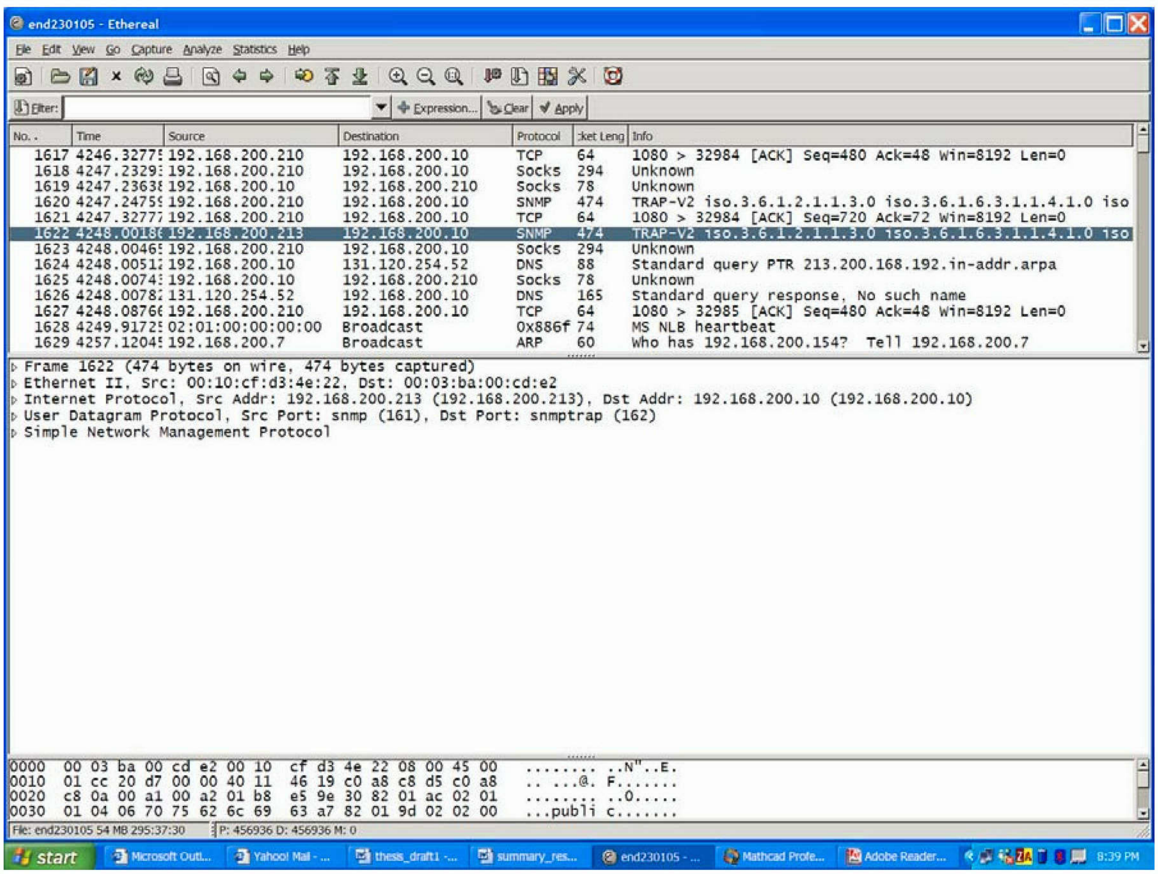

Figure 16. Screenshot of data captured using Ethereal

E. SUMMARY

The configuration of the SONET network and the equipment used were presented in this chapter. The data collection process was also described.

The next chapter provides readers with some background on the queuing theory and self-similarity concepts used for the analysis of the data.

IV. QUEUING THEORY AND SELF-SIMILARITY CONCEPT

A. CHAPTER OVERVIEW

This chapter provides a brief review of discrete random variables. In addition, the queuing equations used in this specific study are highlighted. Lastly, the self-similarity concept, in particular the Hurst parameter is presented.

B. DISCRETE RANDOM VARIABLES

Equations (4.1) to (4.4) define important characteristics of discrete random variables [16]:

Mean: $$E[X] = \mu_x = \sum_{all\,k} k \Pr[x = k] \qquad (4.1)$$

Second Moment: $$E[X^2] = \sum_{all\,k} k^2 \Pr[x = k] \qquad (4.2)$$

Variance: $$\mathrm{Var}[X] = E[(X - \mu_X)^2] = E[X^2] - \mu_X^2 \qquad (4.3)$$

Standard Deviation: $$\sigma_X = \sqrt{\mathrm{Var}[X]}. \qquad (4.4)$$

Using the results of Equations (4.1) and (4.4), the coefficient of variation, an important parameter for queuing analysis, is derived as shown in Equation (4.5). This coefficient gives a normalized measure of variability [16].

Coefficient of Variation: $$\frac{\sigma_X}{\mu_X}. \qquad (4.5)$$

Two important distributions related to queuing theory will be discussed in the next subsection.

1. Exponential Distribution

The exponential distribution has the following distribution and density functions [16]:

$$F(x) = 1 - e^{-\lambda x} \qquad (4.6)$$

$$f(x) = \lambda e^{-\lambda x}. \tag{4.7}$$

Figure 17 and 18 plot the exponential probability density and probability distribution, respectively.

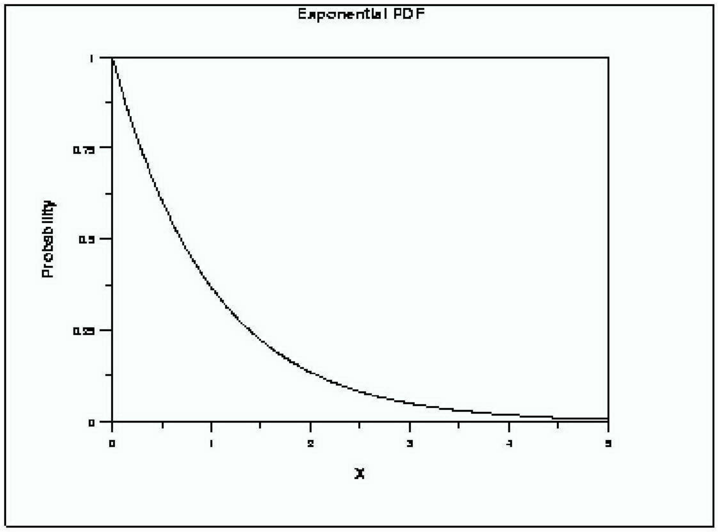

Figure 17. Exponential probability density (From Ref. [17].)

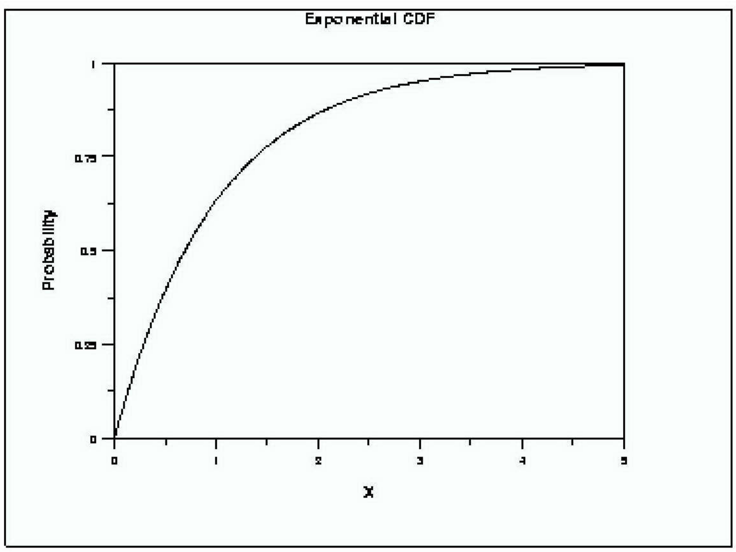

Figure 18. Exponential probability distribution (From Ref. [17].)

Note that the mean of the distribution is equal to its standard deviation:

$$E[X] = \sigma_X = \frac{1}{\lambda}. \tag{4.8}$$

This distribution is important in queuing theory because we can assume that the service time of a network is exponential [16].

2. Poisson Distribution

Another important distribution for queuing analysis is the Poisson distribution. It is used to model the number of events occurring within a given time interval [17]. It is given by:

$$\Pr[X = k] = \frac{\lambda^k}{k!}e^{-\lambda} \tag{4.9}$$

where λ is the shape parameter which indicates the average number of events in a given time interval. Figure 19 plots the Poisson distribution with 4 different λ values.

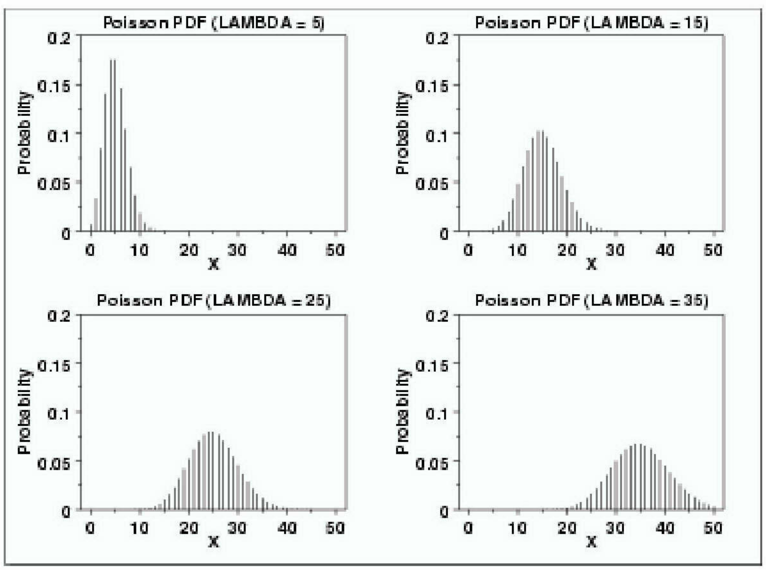

Figure 19. Poisson distribution for λ = 5, 15, 25 and 35 (From Ref. [17].)

The poisson distribution can be applied to arrival rate and are expressed as:

$$\Pr[k \text{ items arrive in the time interval } T] = \frac{(\lambda T)^k}{k!}e^{-\lambda T} \tag{4.10}$$

$$E[\text{number of items to arrive in time interval } T] = \lambda T \tag{4.11}$$

$$\text{Mean arrival rate, in items per second} = \lambda . \tag{4.12}$$

Assuming that the inter-arrival time is exponentially distributed, we can relate to the Poisson process as shown in the equations below:

$$\Pr[\text{Inter-arrival time} < \text{t}] = 1 - e^{-\lambda t} \tag{4.13}$$

$$E[\text{Inter-arrival time}] = \frac{1}{\lambda}. \tag{4.14}$$

From Equation (4.14), the mean inter-arrival time is the reciprocal of the arrival rate [16].

C. QUEUING EQUATIONS

For analysis in the subsequent chapter, the equations in [16] are highlighted as shown below. From (4.14),

$$\lambda = \frac{1}{\text{Mean inter-arrival time}}. \tag{4.15}$$

The service time, T_S, is the packet transmission time of a packet switched system [16]. Therefore, T_S is given by

$$\mathrm{T_S} = \frac{\text{Mean packet size (bytes)} \times 8}{\text{Link Speed}}. \tag{4.16}$$

Thus, the link utilization ρ is derived as shown below:

$$\rho = \lambda T_S. \tag{4.17}$$

D. SELF-SIMILARITY CONCEPT

Exponential and Poisson distributions are commonly used in queuing analysis. However, “Poisson-like” models suggest that traffic is smooth with predictable bursts [18]. This assumption is usually not valid for most data traffic. A number of studies demonstrate that the traffic patterns of data are more self-similar than Poisson [16], [19], [20]. Self-similarity provides a more accurate traffic analysis and takes into account the burstiness of traffic. In this section, an overview of the Hurst parameter and queue depth will be discussed.

1. Hurst Self-similarity Parameter

The Hurst parameter, H, is a measure of self-similarity. A traffic is said to be self-similar if the value of H is high, i.e., $H \gg 1.0$. There are many approaches to esti-

mate H. In this study, the variance-time plot is used to analyze the data captured. Using this approach, H is estimated by analyzing the variances of aggregated processes, (x^m), where m is an integer representing the number of samples considered in a given sample window [5]. From [16], the variance obeys the following for large m:

$$\mathrm{Var}(x^{(m)}) \sim \frac{\mathrm{Var}(x)}{m^{\beta}} \tag{4.18}$$

where β is defined as:

$$H = 1 - (\beta/2)\,. \tag{4.19}$$

Taking the logarithm on both sides of Equation (4.18),

$$\log[\mathrm{Var}(x^{(m)})] \sim \log[\mathrm{Var}(x)] - \beta\log(m) \tag{4.20}$$

A variance-time plot is obtained by plotting $\log[\mathrm{Var}(x^m)]$ vs $\log(\mathrm{m})$. β is obtained from the gradient of the plot. H is then calculated using Equation (4.19).

2. Queue Depth for Self-similar Traffic

Self-similar traffic is characterized to be bursty in nature [16]. In a network scenario, this burstiness in the traffic causes network buffer to overflow, if not properly allocated. Thus, in this study, the queue depth or the buffer requirement is calculated. The queue depth of a network, q, is defined as a function of the mean utilization, ρ and H as shown in the equation below [21]:

$$q = \frac{\rho^{1/2(1-H)}}{(1-\rho)^{H/1-H}} \tag{4.21}$$

Note that Equation (4.21) is valid for networks with fixed length packets. In this study, it is reasonable to use this equation as an approximation since the SNMP and the Socks packet lengths have fairly low variance.

E. SUMMARY

This chapter briefly reviewed the characteristics of random variable and, specifically, the exponential and Poisson distributions. The queuing equations used in the analysis of this thesis were defined. The self-similarity concept, in particular the Hurst parameter, was introduced. The queue depth and link utilization were also discussed.

The next chapter presents a detailed statistical traffic analysis on the data captured.

V. TRAFFIC ANALYSIS AND FINDINGS

A. CHAPTER OVERVIEW

This chapter presents the observations and analysis from the data captured under load conditions. The first section covers the observations from initial traffic analysis using Ethereal. This is followed by a more detailed analysis using statistical tools discussed in Chapter IV. The results from the analysis are then compared to the results obtained under no-load conditions in [5].

B. OBSERVATIONS

Web traffic was loaded in the SONET network throughout the entire data capturing process. The data exchange between the CTM 4.6 Server and the managed NEs was captured from December 29, 2004 to January 7, 2005 over a period of 255 hours. Table 4 summarizes the traffic captured. The types of traffic that are of interest to our analysis are the Socks, TCP and SNMPv2 traffic. Other traffic collected from the process includes Address Resolution Protocol (ARP), User Datagram Protocol (UDP) and Domain Name Server (DNS) packets which are not relevant to our study. In addition, the table also shows the data statistics from [5] for comparison and will be discussed later.

Type of Traffic Number of Packets	Without Load in the SONET Network	With Load in the SONET Network	
	July 20 – July 30 2004 (From Ref. [5].)	December 29, 2004 – January 7, 2005	January 11 – January 21, 2005
Socks communications between CTM and the managed NEs	203,278	94,916	126,008
TCP overhead for CTM's Socks communications	260,461	107,446	130,884
SNMPv2 traffic	7,364	4,332	5,301
Other communications on the network	193,333	98,138	121,180
Total packets captured on the network	664,436	304,832	383,373

Table 4. Summary of traffic captured on CTM 4.6 Server with and without load in the SONET network

From Ethereal, it was observed that the CTM 4.6 uses CISCO's proprietary Socks protocol to communicate with the NEs. From the deciphered payload section of Ethereal, General Inter-ORB Protocol (GIOP) was determined to be implemented as part of the Socks protocol. Ethereal also showed that CTM 4.6 uses *getbulk* operation in SNMPv2 to collect a large amount of information from the NEs. SNMPv2 "trap" packets sent by the NEs were also observed. In addition, TCP traffic which includes the overhead for setting up and tearing down TCP connections, TCP acknowledgements and retransmission were observed. Note that these TCP traffic will be collectively termed as Ethernet traffic. Thus far, all these observations coincide with the findings in an earlier thesis [5] by Wee Shoong Lim.

From Table 4, it is interesting to note that the total amount of data collected over the almost similar period of time under loaded conditions is approximately half that collected under no-load condition. To confirm this observation, another run was performed between January 11 and January 21, 2005, for the same period of time. During this run, the simulated web traffic on the SONET ring was interrupted and halted for 2 days. The results obtained were tabulated in Table 4. Comparing the two results, more traffic was captured on the second run. Close inspection of the data captured revealed that the exchange of SNMP and Socks traffic between CTM and the managed NEs account for the increase in the overall traffic. Therefore, based on the preliminary assessment, the results suggest that less management information will be exchanged when the SONET network is fully loaded. This is possible since it may not be necessary for each network element to update its heartbeat to the CTM when it is not idling. This is typical for protocols supporting large networks to ensure efficiency and performance.

C. STATISTICAL ANALYSIS

The inter-arrival time between packets and packet size are important parameters for understanding and modeling each type of traffic. The inter-arrival time between packets is calculated by the difference in arrival time between adjacent packets ("Time" column in Figure 16). The packet size can be extracted directly from the data captured ("Length" column as shown in Figure 16). In this study, an unpublished MathCad pro-

gram written by Lieutenant James Young was used to calculate these values and generate data samples to obtain the distribution plots. Note that the analysis in this section is based on the data captured between December 29, 2004 and January 7, 2005. The second run only served to confirm the observation of less packets being captured under load conditions as compared to the scenario without traffic traversing in the SONET ring. Moreover, the data from the second run is incomplete given the 2-day interruption to be able to establish an accurate analysis on the effect of traffic load in the SONET ring on the network management tool.

1. Inter-arrival Time Distribution

The inter-arrival distributions for each type of traffic are plotted in Figures 20 to 23.

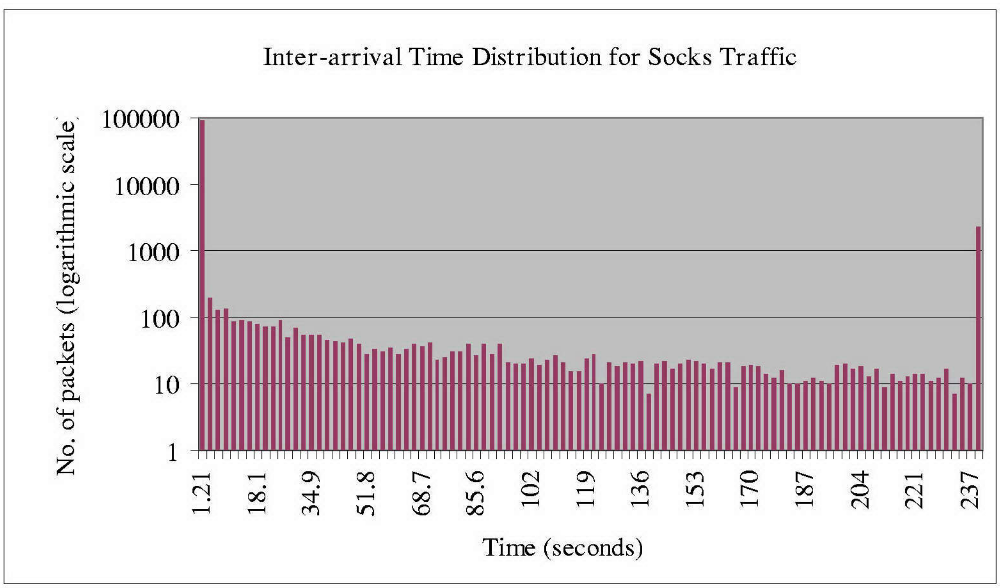

Figure 20. Inter-arrival time distribution for Socks traffic

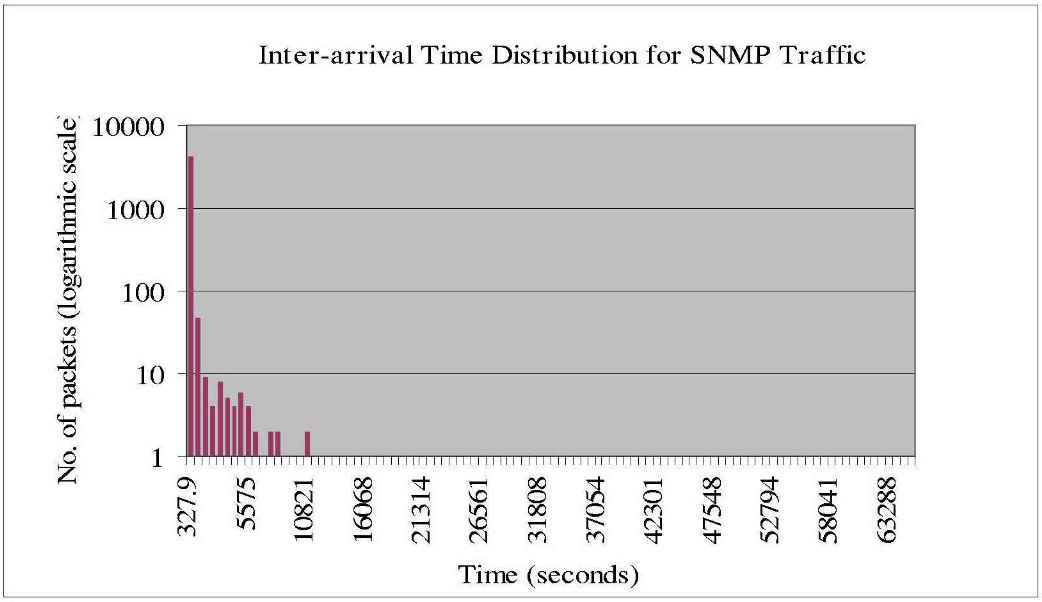

Figure 21. Inter-arrival time distribution for SNMP traffic

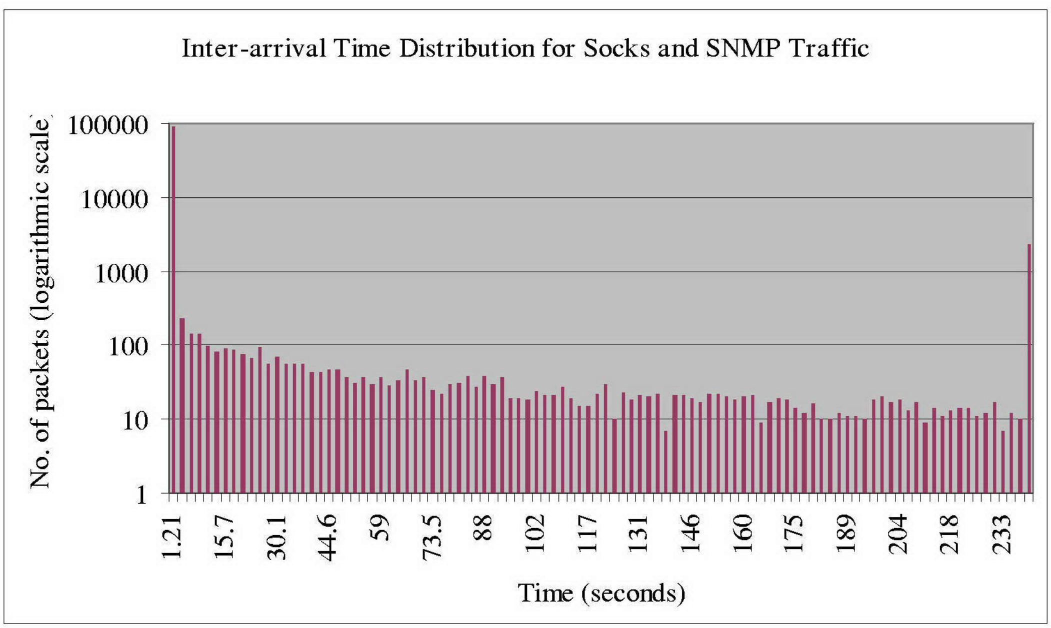

Figure 22. Inter-arrival time distribution for Socks and SNMP traffic

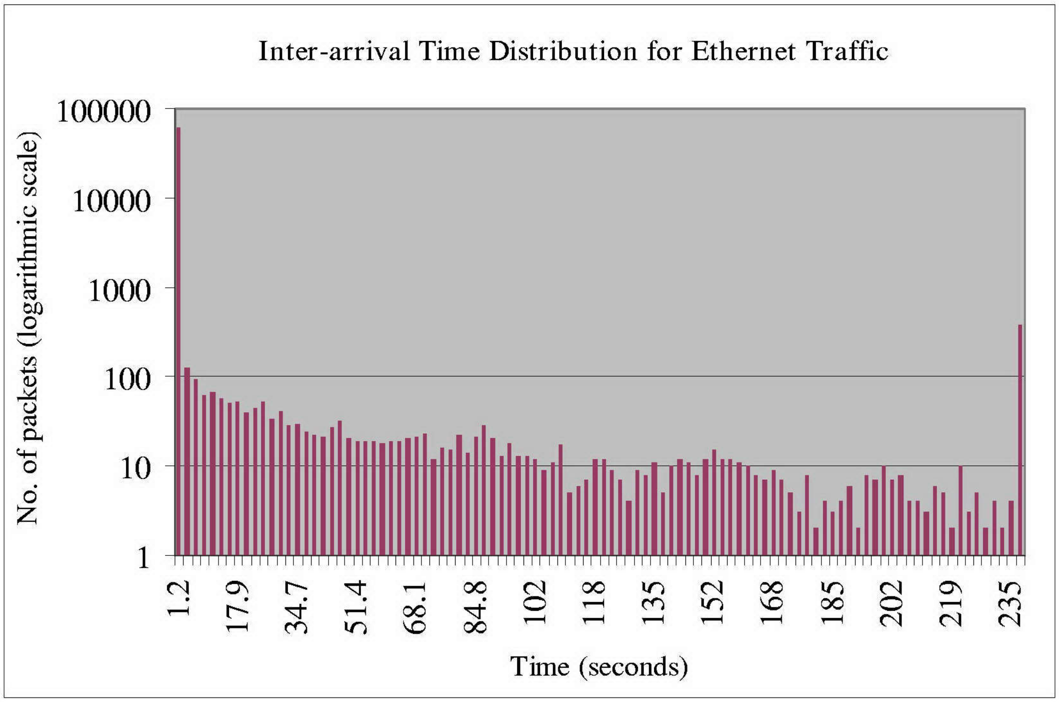

Figure 23. Inter-arrival time distribution for Ethernet traffic

Figures 20, 22 and 23 demonstrate a heavy-tailed distribution, thus inferring long-range dependence and self-similarity in the traffic [22]. In addition, the majority of the packets arrive within a relatively short inter-arrival time (~ 1 second). For Figure 21, the distribution for SNMP traffic resembles that of the exponential distribution with a linear decay rate, $\lambda \leq 1$. It is also seen that SNMP traffic has a longer inter-arrival time than the other traffic.

Using Equations (4.1) to (4.5), the mean, variance, and coefficient of variation of the inter-arrival time distributions were computed using MathCad and tabulated in Table 5. From Table 5, it is observed that all the coefficients of variation are greater than 1 and thus confirms our earlier deduction of a heavy-tail distribution. Table 6 shows the results obtained under the no-load condition (extracted from [5]). Comparing the results from Table 5 and 6, it can be seen that all of the traffic, regardless of the load conditions, have high coefficients of variation, implying a uniformly consistent strong tail.

Type of Traffic	Mean (s)	Variance (s^2)	Coefficient of Variation
Socks	8.2	1.633×10^3	4.927
SNMP	179.533	4.536×10^6	11.863
Socks & SNMP	7.842	1.563×10^3	5.041
Ethernet	3.213	542.584	7.249

Table 5. Tabulated statistics for inter-arrival time distribution under load conditions

Type of Traffic	Mean (s)	Variance (s^2)	Coefficient of Variation
Socks	4.553	772.087	6.103
SNMP	120.043	627080.020	6.597
Socks & SNMP	4.394	745.556	6.215
Ethernet	1.965	323.759	9.159

Table 6. Tabulated statistics for inter-arrival time distribution under a no-load condition (After Ref. [5].)

By substituting the mean values found in Table 5 into Equation (4.15), the arrival rate, λ, for the inter-arrival distribution was computed. The calculated values are compiled in Table 7. The values of λ for the no-load condition (extracted from [5]) are also included in Table 7. Comparing the results, it can be seen that all the traffic tends to arrive at a faster rate under the no-load condition. Thus the λ value again suggests that there is less data exchanged between the CTM and the managed NEs when the SONET network is loaded with traffic.

Type of traffic	λ (s^{-1})	
	With Load	Without Load (From Ref. [5].)
Socks	0.122	0.220
SNMP	0.00557	0.008
Socks & SNMP	0.128	0.228
Ethernet	0.311	0.509

Table 7. Tabulated value of arrival rate, λ, for the inter-arrival distribution with and without load conditions

2. Packet Length Distribution

The packet length distributions of each type of traffic are plotted in Figure 24 to 27.

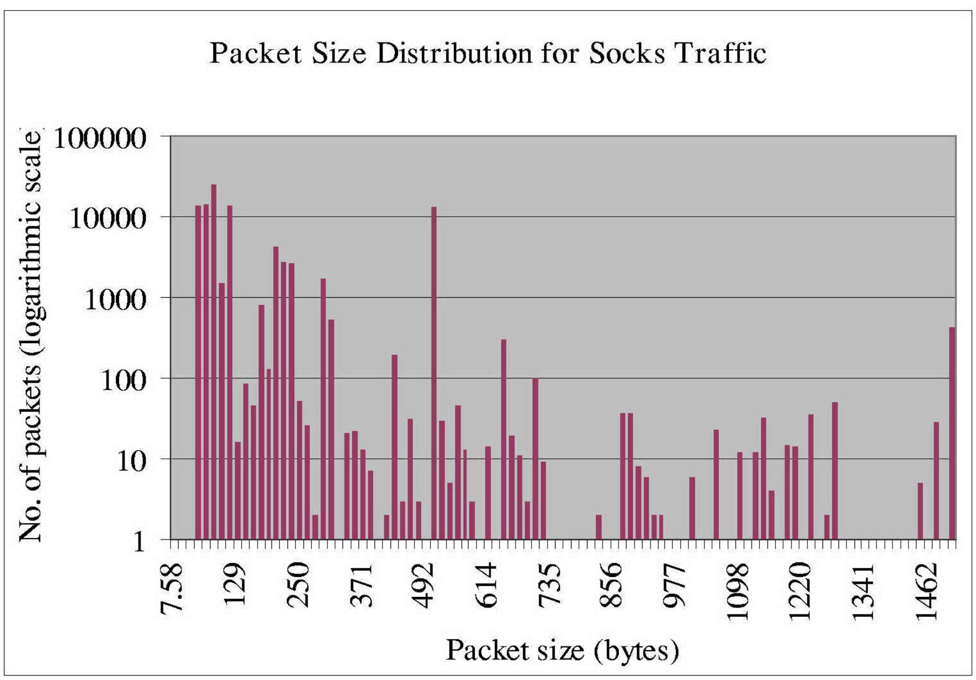

Figure 24. Packet size distribution for Socks traffic

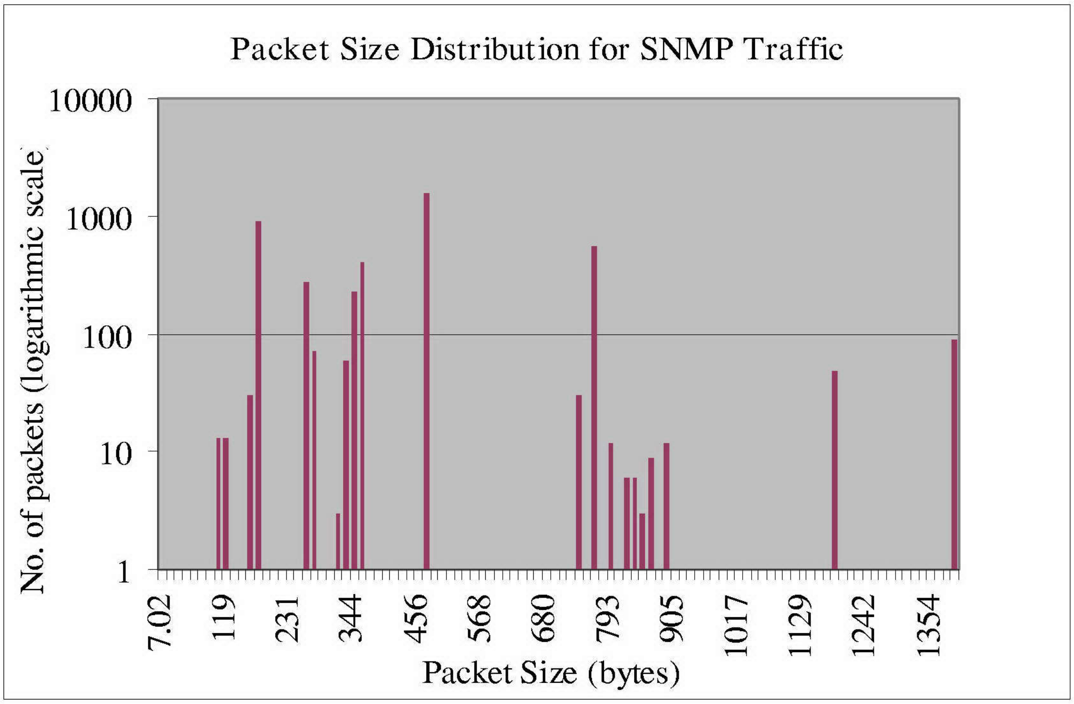

Figure 25. Packet size distribution for SNMP traffic

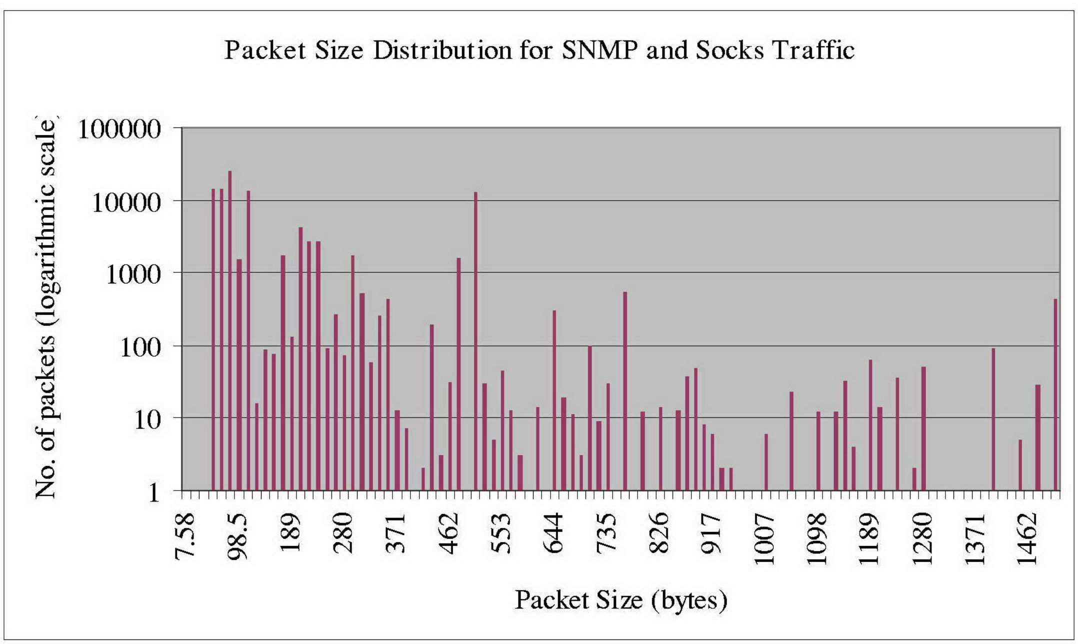

Figure 26. Packet size distribution for Socks and SNMP traffic

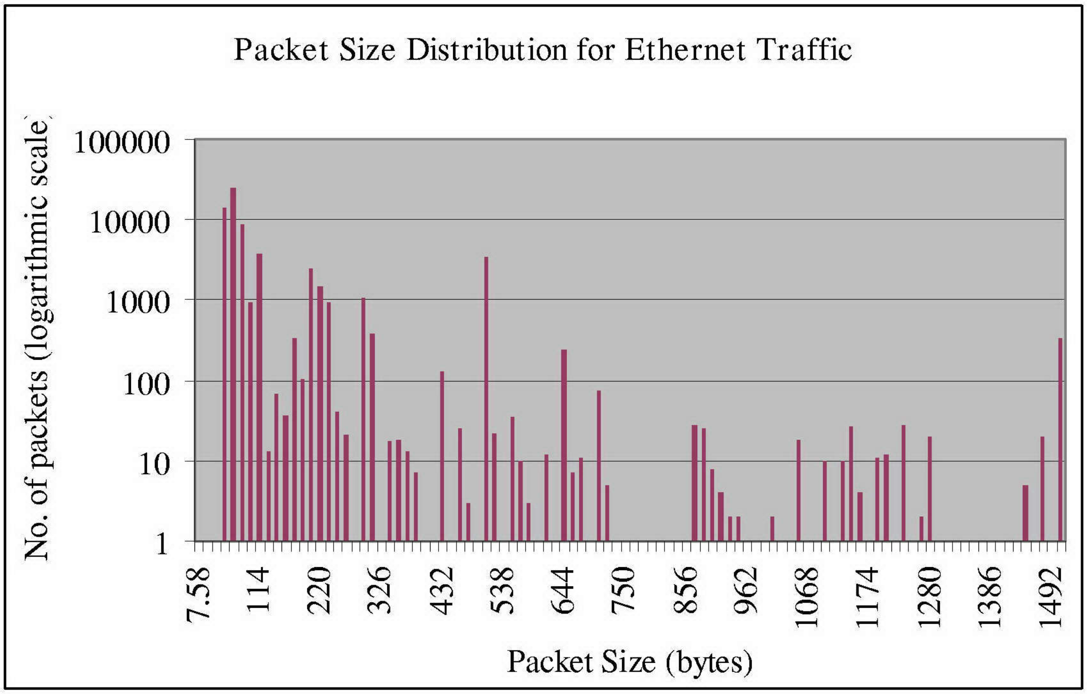

Figure 27. Packet size distribution for Ethernet traffic

Figures 24, 26 and 27 show a slight resemblance to exponential distribution with a significant tail. In addition, it is observed that almost 70% of the Socks packets are less than 100 bytes, i.e., the majority of the packets are small in size. On the other hand, it is seen from Figure 25 that the packet size of SNMP is generally larger than the Socks packet size (> 150 bytes). Using Equations (4.1) to (4.5), the mean, variance, and coefficient of variation of the packet size distributions are computed using MathCad as shown in Table 8.

Type of Traffic	Mean (bytes)	Variance (bytes^2)	Coefficient of Variation
Socks	171.864	3.581×10^4	1.101
SNMP	441.173	6.124×10^4	0.561
Socks & SNMP	183.623	3.995×10^4	1.089
Ethernet	125.262	2.794×10^4	1.334

Table 8. Tabulated statistics for packet size distribution

Next, the service time T_s was calculated by substituting the mean values in Table 8 into Equation (4.16) and is tabulated in Table 9. The type of link and speed for each type of traffic is also recorded in Table 9. Table 9 also presents the T_s values obtained under no-load conditions (extracted from [5]). Comparing both results, it can be seen that the service time under load and no-load conditions are almost similar.

Type of Traffic	Type of Link / Speed	T_S under Load Conditions	T_S under No-Load Condition (From Ref. [5])
Socks	SDCC / 192kbps	7.161 ms	6.044 ms
SNMP	SDCC / 192kbps	18.382 ms	18.967 ms
Socks & SNMP	SDCC / 192kbps	7.651 ms	6.496 ms
Ethernet	Ethernet / 100Mbps	10.021 μs	8.214 μs

Table 9. Tabulated values of service time, T_S, for the packet size distributions under load and no-load conditions

3. Link Utilization

The link utilization was computed by substituting the values in Table 7 and 9 into Equation (4.17). The link utilizations for four NEs under load conditions are calculated and tabulated in Table 10. The link utilization under the no-load condition is also included in Table 10 (extracted from [5]).

Type of Traffic	Type of Link / Speed	Link Utilization under Load Conditions	Link Utilization under No-Load Condition (From Ref. [5].)
Socks	SDCC / 192kbps	8.736×10^{-4}	1.33×10^{-3}
SNMP	SDCC / 192kbps	1.024×10^{-4}	1.58×10^{-4}
Socks & SNMP	SDCC / 192kbps	9.793×10^{-4}	1.48×10^{-3}
Ethernet	Ethernet / 100Mbps	3.117×10^{-6}	4.18×10^{-6}

Table 10. Tabulated link utilization for 4 NEs under load and no-load conditions

Next, extrapolation of the results obtained in Table 10 was performed to derive the link utilization for 2500 NEs (the maximum capacity of CTM 4.6). The results are tabulated in Table 11. The link utilization under the no-load condition (extracted from Ref. [5]) is also presented in Table 11 for comparison. From Table 11, it is observed that the CTM 4.6, which has both Socks and SNMP on SDCC, utilizes about 61% of the SDCC capacity when managing 2500 NEs under load conditions. This provides a spare capacity of 39% on the SDCC, compared to only 18% under the no-load condition. It is interesting to note that the preliminary results show the network management protocol employed by CTM 4.6 is able to handle 2500 NEs efficiently even under load conditions. More detailed analysis using the queue depth [22] will be required to determine if the CTM 4.6 is capable of managing this large number of NEs by taking into account the burstiness of the traffic. In addition, from Table 10, it is observed that the link utilization of Ethernet traffic is insignificant as found in [5].

Type of Traffic	Type of Link / Speed	Link Utilization under Load Conditions	Link Utilization under No-load Condition (From Ref. [5])
Socks	SDCC / 192kbps	0.546	0.830
SNMP	SDCC / 192kbps	0.064	0.099
Socks & SNMP	SDCC / 192kbps	0.612	0.926
Ethernet	Ethernet / 100Mbps	1.948×10^{-3}	2.62×10^{-3}

Table 11. Tabulated link utilization for 2500 NEs under load and no-load conditions

4. Estimation of Self-Similarity

Figures 28 to 31 show the variance inter-arrival plots for different types of traffic. The variance packet size plots for different types of traffic are shown in Figures 32 to 35. Note the value of $\log(m)$ = 0, 1, 1.5, 2, 2.5 and 3 correspond to the values of m = 1, 10, 32, 100, 320 used in Mathcad to generate data points for the variance-index plots. A lin-

ear trendline indicated in red is added in each plot. The function of this straight line corresponds to Equation (4.20). It is, however, interesting to note that the best-fit trendline for Figures 28 and 30 is a second-order polynomial. Thus, we can conclude that the Socks and combined Socks and SNMP traffic are highly self-similar in large time-scale and less self-similar in smaller time-scale.

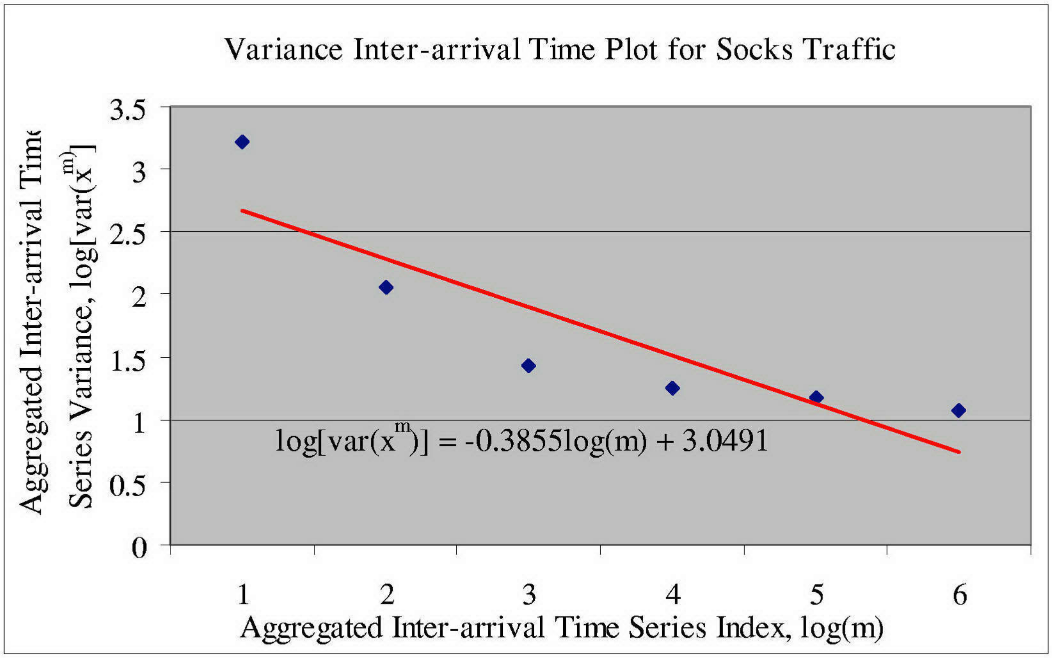

Figure 28. Variance inter-arrival time plot for Socks traffic

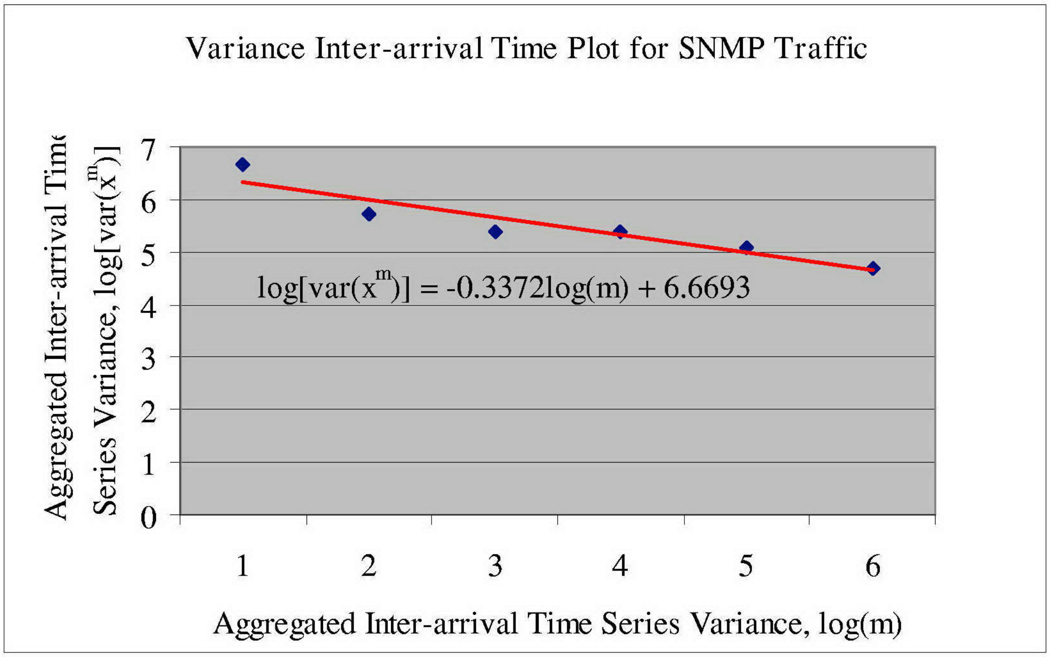

Figure 29. Variance inter-arrival time plot for SNMP traffic

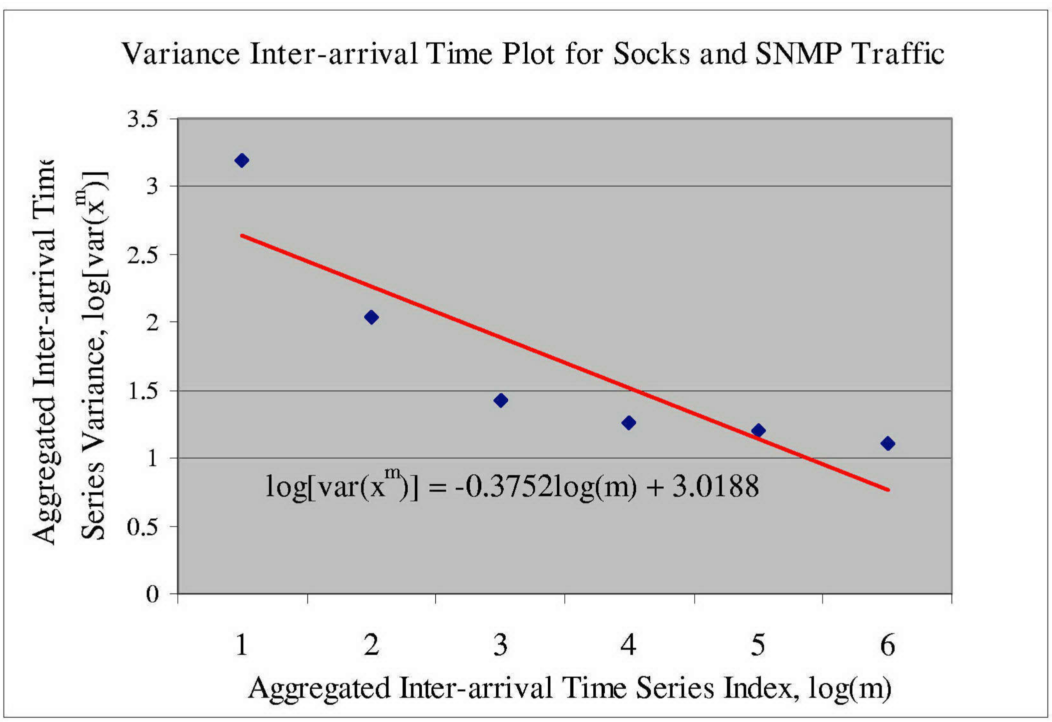

Figure 30. Variance inter-arrival time plot for Socks and SNMP traffic

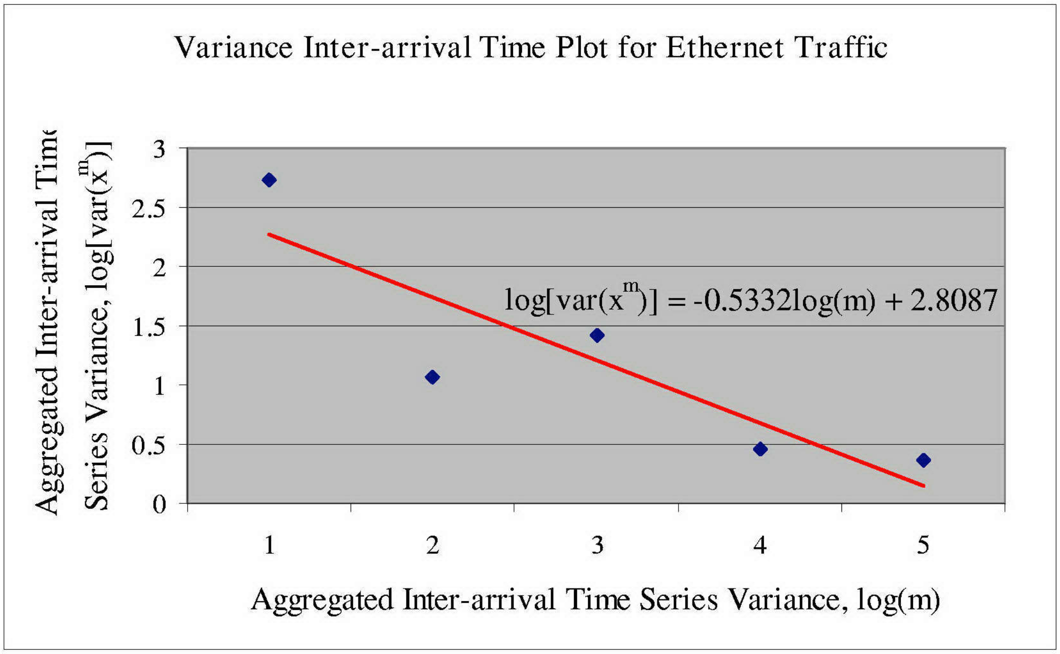

Figure 31. Variance inter-arrival time plot for Ethernet traffic

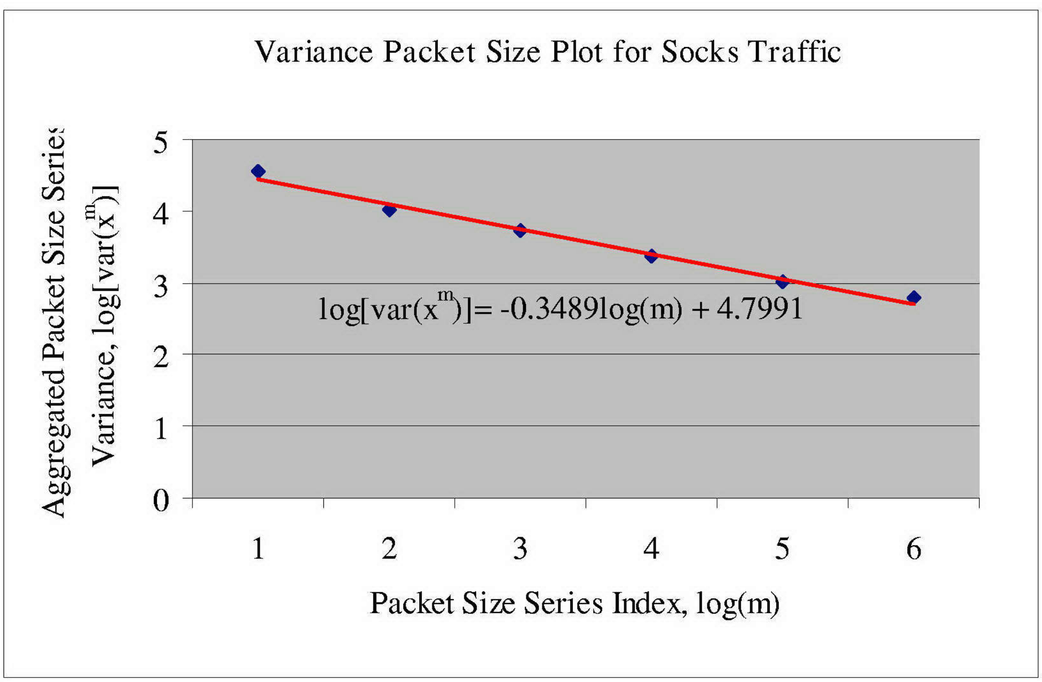

Figure 32. Variance packet size plot for Socks traffic

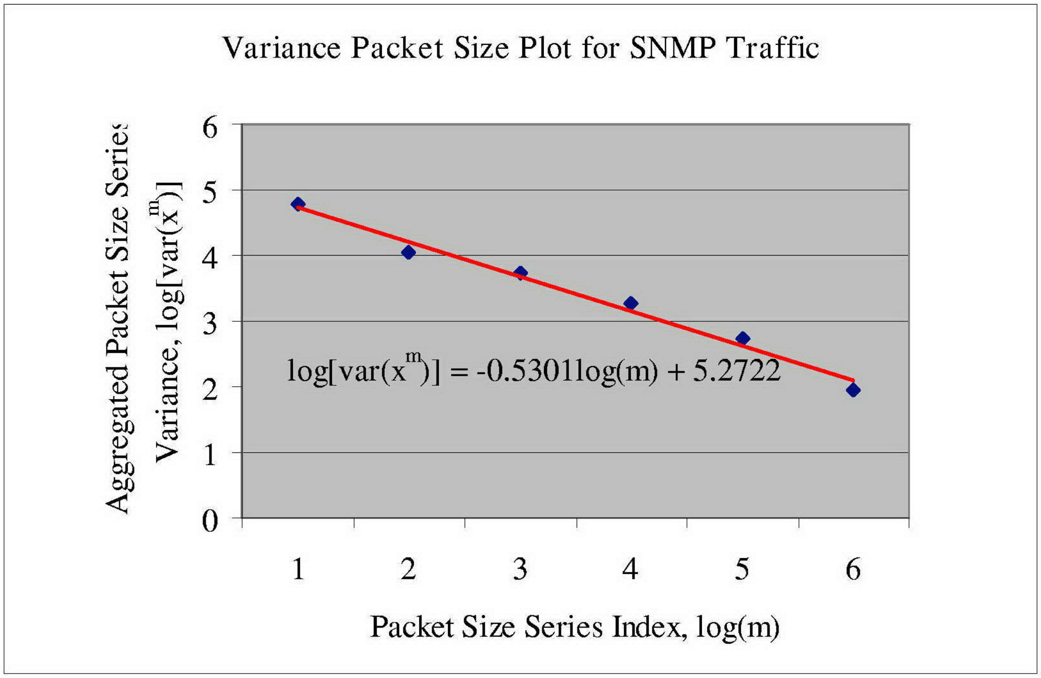

Figure 33. Variance packet size plot for SNMP traffic

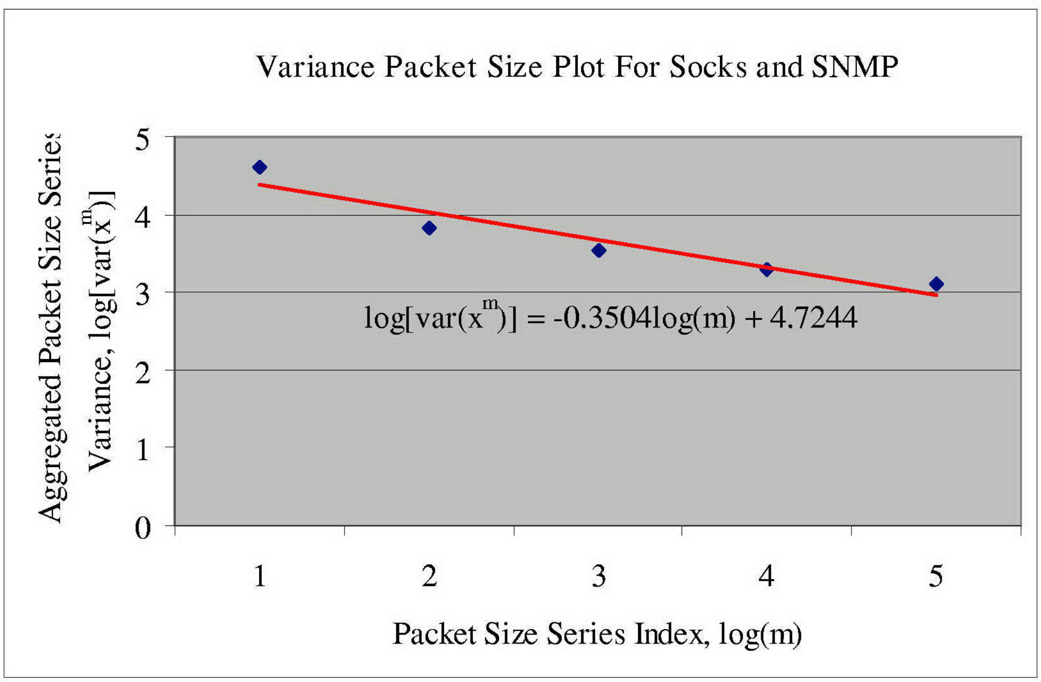

Figure 34. Variance packet size plot for Socks and SNMP traffic

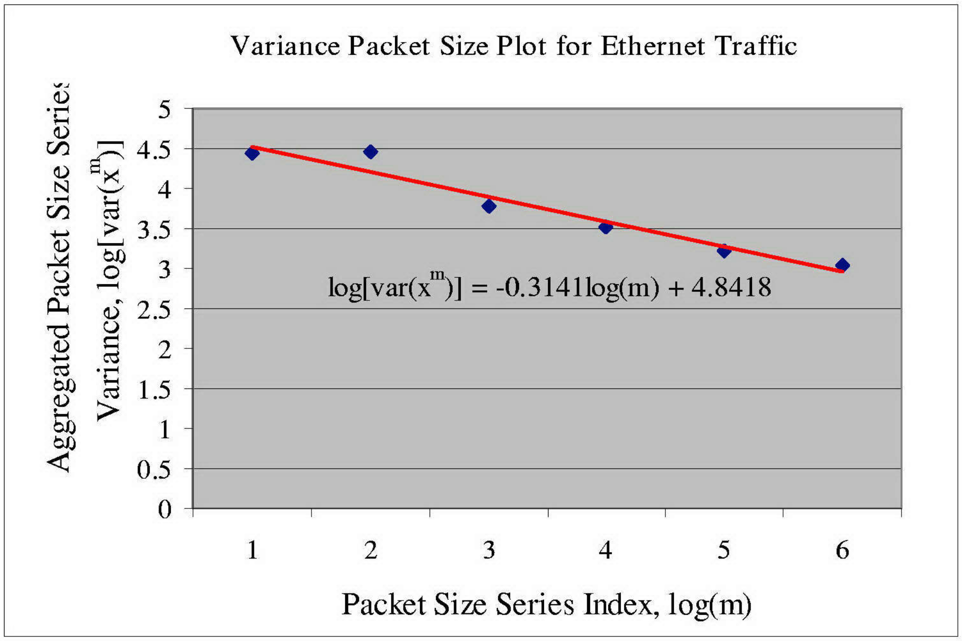

Figure 35. Variance packet size plot for Ethernet traffic

Using Equation (4.20), the value of β can be obtained from the gradient of the line. The values of H are then computed by substituting β into Equation (4.19). Table 12 tabulates the values of β and the corresponding values of H under the load and no-load conditions (results for no-load conditions are extracted from [5]). From Table 12, it can be seen that all the traffic (Socks, SNMP and Ethernet) under load conditions have large value of H ($H > 0.5$), and thus have a high degree of self-similarity. These high values of H also indicate that Socks, SNMP and Ethernet traffic are bursty [22]. These results coincide with our earlier results obtained in the distributions plots. Comparing with the results obtained under no-load conditions, it can be seen that most of the traffic except for Socks and, combined Socks and SNMP traffic exhibits similar characteristics (i.e., highly self-similar and bursty).

Type of Traffic	Under Load Conditions		Under No-Load Condition (From Ref. [5].)	
	β	H	β	H
Socks Traffic (Inter-arrival time)	0.3855	0.8073	0.99	0.505
Socks Traffic (Packet size)	0.3489	0.8256	0.8867	0.5567
SNMP (Inter-arrival time)	0.3372	0.8314	0.5952	0.7024
SNMP Traffic (Packet size)	0.5301	0.7349	0.1869	0.9066
Socks & SNMP(Inter-arrival time)	0.3752	0.8124	0.9785	0.5108
Socks & SNMP(Packet size)	0.3504	0.8248	0.7547	0.6227
Ethernet (Inter-arrival time)	0.5332	0.7334	0.6324	0.6838
Ethernet (Packet size)	0.3141	0.8430	0.395	0.8025

Table 12. Tabulated value of β and H under load and no-load conditions

5. Effects of Self-Similarity on Queue Depth

Figures 36 to 38 plot the mean utilization of the network, ρ, versus the queue depth, q, in Equation (4.21) using the values of H in Table 12. Different scales for q are applied to each plot. As can be seen in the figures, the queue buffer requirements begin to increase drastically at lower levels of utilization for higher values of H [16]. From Figure 36, it can be seen that for $\rho \leq 0.38$, $q \leq 1$ for all traffic under load conditions. This value is similar to the ρ value obtained under the no-load condition in [5]. From Figure 37, it would require $q = 12$ to accommodate the combined Socks and SNMP traffic (inter-arrival time) when managing 2500 NEs. Comparing these results to [5], the queue size required when the SONET network is loaded is approximately ten times less than when there is no traffic in the SONET network.

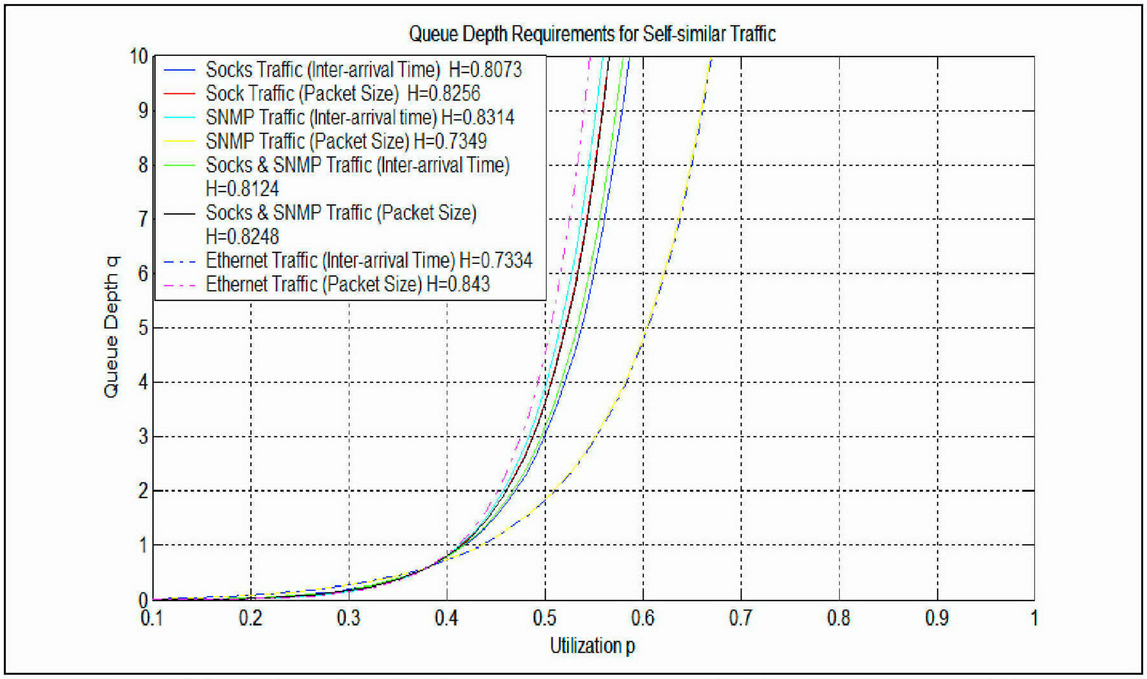

Figure 36. Plot of utilization, ρ versus queue depth, q (scale to $q = 10$)

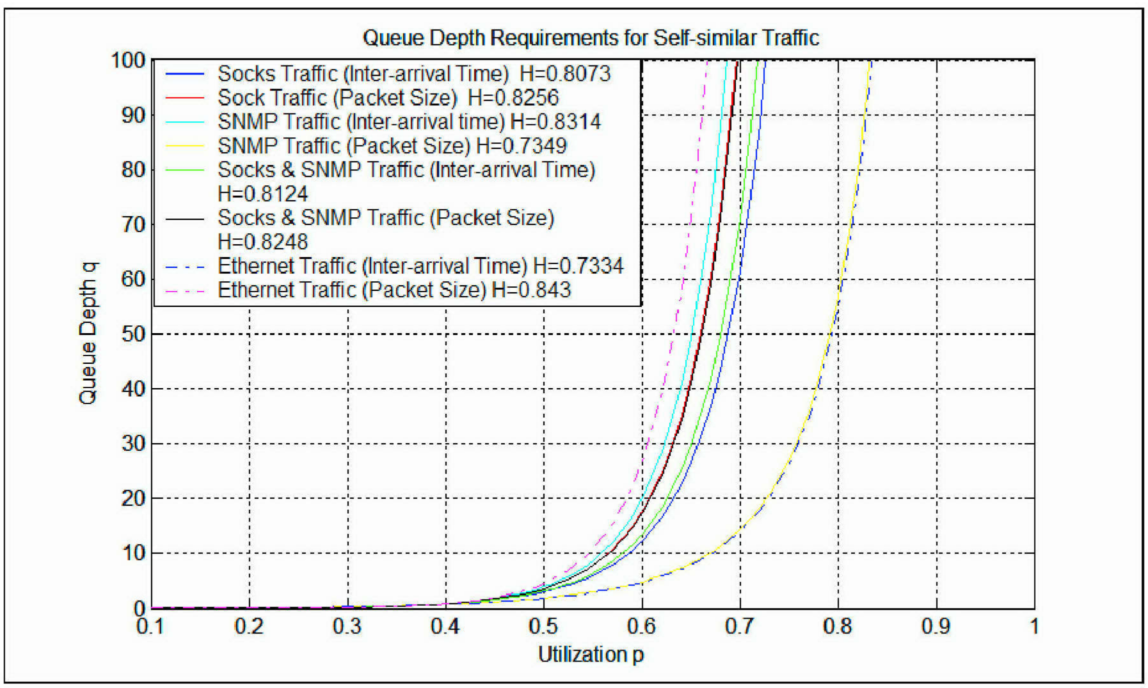

Figure 37. Plot of utilization, ρ versus queue depth, q (scale to $q = 100$)

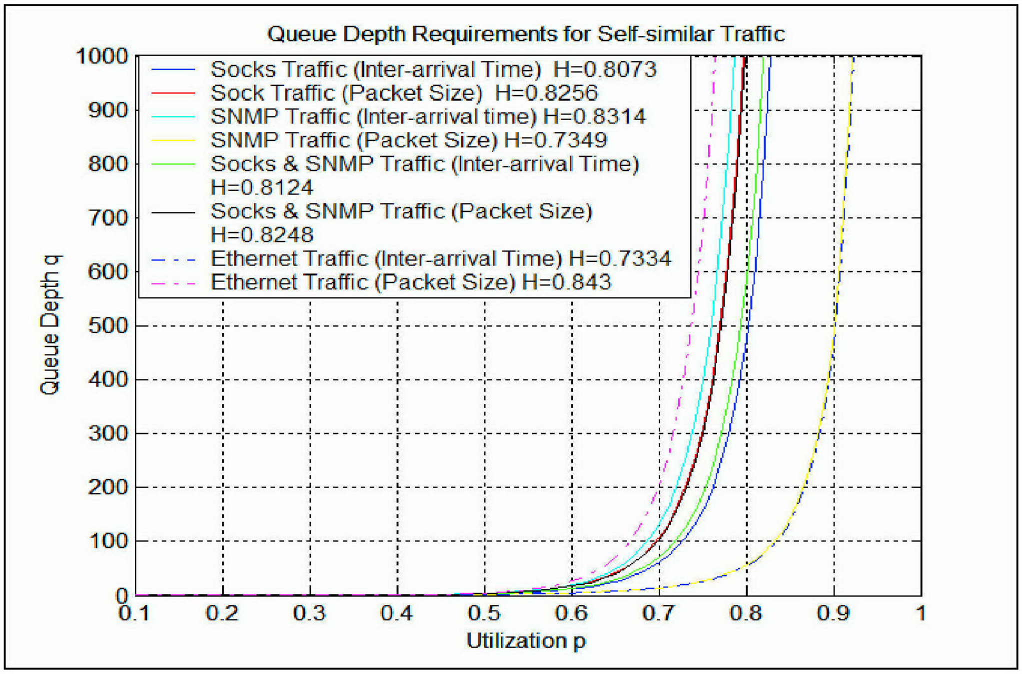

Figure 38. Plot of utilization, ρ versus queue depth, q (scale to $q = 1000$)

The maximum number of NEs required to obtain utilization of 0.38 are then tabulated in Table 13. Table 13 also presents the results extracted from [5] for comparison. It can be seen that CTM 4.6 can manage a higher number of NEs under load conditions than under the no-load conditions. This is possible since less management data is exchanged as shown in Table 4. It is also observed that Ethernet traffic has no impact to the network. In addition, from Table 13, q will be reduced to 1 if only 1552 NEs are managed instead (compared to 1027 NEs under the no-load condition in [5]). Thus, depending on the available buffer size, it is possible for CTM 4.6 to manage 2500 NEs as stated in the specifications but it is still not advisable.

Type of Traffic	Maximum Number of NEs	
	Under Load Conditions	Under No-load Conditions (From Ref. [5].)
Socks	1739	1142
SNMP	14843	9620
Socks & SNMP	1552	1027
Ethernet	487648	360000

Table 13. Maximum number of NEs required to obtain a utilization of 0.38

D. SUMMARY

Data captured were analyzed using statistical tools and self-similarity concepts. The results obtained were discussed and compared to the results in [5]. In particular, the difference in time interval, packet length and link utilization of the management data were evaluated. The detailed analysis demonstrated that less management data was exchanged when the SONET network was fully loaded. In addition, it is recommended that CTM 4.6 be used to manage not more than 1552 NEs for safe operation.

The following chapter summarizes and concludes the study. In addition, more areas that have not been explored due to lack of resources and time will be discussed.

VI. CONCLUSION AND FURTHER RESEARCH AREAS

A. CHAPTER OVERVIEW

The chapter summarizes and concludes the research in this study. Related research areas are also proposed for possible extension to the current study.

B. CONCLUSION

A SONET network was set up in the Advanced Network Laboratory. To study the effect of the traffic loading in the SONET network on the CTM 4.6, Avalanche Smartbits, a traffic generator, was installed and configured. Data was then passively captured from the CTM 4.6 server machine via Ethereal, a packet sniffer. For the relevance of the study, only Socks, SNMPv2 and TCP traffic from CTM 4.6 were extracted and analyzed.

The results gathered from Ethereal were compared to the findings obtained in [5]. Preliminary observations showed that less traffic was exchanged between the CTM and the managed NEs when the SONET network is loaded. Close inspection revealed that more Socks and SNMP traffic were transferred when there is no user traffic on the network.

Further analysis on the inter-arrival time and packet size distribution were performed. From the inter-arrival distribution, all the traffic (Socks, SNMPv2 and Ethernet traffic) demonstrated long range dependence and self-similarity, regardless of the load conditions in the SONET network. However, it was observed that management data was exchanged at a shorter time interval without user traffic in the SONET network. For the packet size distribution, it was found that the packet size of all traffic were almost similar under different load conditions.

The Hurst parameter was then used to estimate the self-similarity of all the traffic. Using the Variance-Index Plot approach, large values of H were found for all the traffic, thus indicating that the traffic is self-similar and bursty in nature. These results were similar to [5] except for Socks and combined Socks and SNMP traffic.

Link utilization was derived for all the traffic. In particular, CTM 4.6's Socks and SNMP traffic had a link utilization of 0.612 when CTM 4.6 was used to manage 2500 NEs. This value was much lower compared to the high utilization of 0.926 obtained in [5] under the no-load condition in the SONET network. Though the utilization was lower in the case of having user traffic in the network, the high Hurst parameter value computed may pose a problem for the CTM 4.6 while managing 2500 NEs.

A network utilization versus queue depth graph was plotted to determine the number of NEs the CTM could realistically manage, taking into account the burstiness of the traffic. From the plot, it is recommended that the CTM 4.6 manages up to a maximum of 1552 NEs, operating within a utilization of 0.38 under load conditions in the SONET network to prevent queuing buffer overflow (compared to 1027 NEs under the no-load condition in the SONET network).

In conclusion, the objectives of this study were met. It is hoped that the results obtained would aid service providers in planning and managing SONET networks.

C. FURTHER RESEARCH AREAS

Due to the lack of required resources or time, a number of areas were not examined and are discussed in the following paragraphs.

1. Investigating the Effects with Failure in the SONET Network

In this study, management data were captured between the CTM 4.6 and the four managed NEs. The NEs in this case are always up and working properly. This, however, is an ideal situation. More management data may be exchanged in the event of a failure in one or more NEs. Due to the time constraints, it was not possible to shut down the NEs randomly so as to capture the traffic for verification. A study can be done to investigate the effects of failures in the SONET network on the management tools.

2. Investigating the Traffic on SDCC

In this study, the traffic coming off the SDCC was captured from the Ethernet network. Although anecdotal observations suggest that the data captured on the Ethernet network sufficiently represents the traffic on the SDCC, extra overhead may be incurred by the transiting SONET switches across the IP network. This may affect the accuracy of the analysis. Due to the faulty equipment for capturing the traffic on SDCC, this area was not explored.

3. Use of Other Vendors' EMS

Beside the CISCO's CTM 4.6, there are other third-party EMSs available in the commercial market (e.g., InCharge from Smarts [23], or Navis from a joint partnership between Lucent and Micromuse [24]). A preliminary evaluation was conducted to determine the interoperability of the CISCO ONS15454s with the other EMSs. It was found that the InCharge from Smarts is a possible alternative to CTM 4.6. However, due to limited financial resources, the EMS was not purchased. It would be interesting to compare the performance of the third's party EMS against the CISCO CTM 4.6.

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